U.S. DEPARTMENT OF COMMERCE
National Technical Information Service
PB-272 519

Potential Radioactive Pollutants Resulting from Expanded Energy Programs

Stanford Research Inst, Menlo Park, Calif

Prepared for

Environmental Monitoring and Support Lab, Las Vegas, Nev

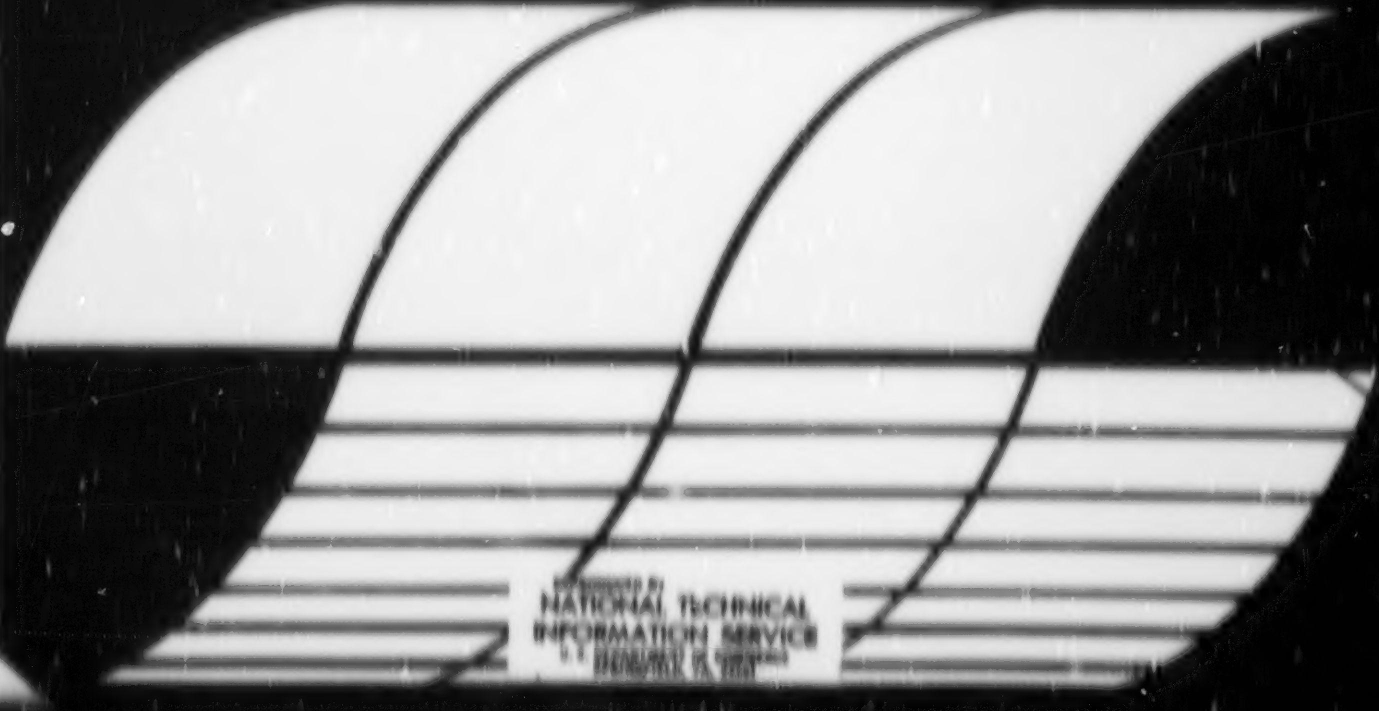
Aug 77

EPA

PB 272 519

POTENTIAL RADIOACTIVE POLLUTANTS RESULTING FROM EXPANDED ENERGY PROGRAMS

Interagency
Energy-Environment
Research and Development
Program Report



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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.
EPA-600/7-77-082

2.

3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE
POTENTIAL RADIOACTIVE POLLUTANTS RESULTING FROM EXPANDED ENERGY PROGRAMS

5. REPORT DATE
August 1977

6. PERFORMING ORGANIZATION CODE

7. AUTHOR(S)
Hong Lee, Thomas O. Peyton (Greenfield Attaway and Tyler, Inc.), Robert V. Steele, and Ronald K. White

8. PERFORMING ORGANIZATION REPORT NO.
CRESS No. 6

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Center for Resource and Environmental Systems Studies
Stanford Research Institute
333 Ravenswood Avenue
Menlo Park, California 94025

10. PROGRAM ELEMENT NO.
1NE 625

11. CONTRACT/GRANT NO.
68-01-2375

12. SPONSORING AGENCY NAME AND ADDRESS
U.S. Environmental Protection Agency-Las Vegas
Office of Research and Development
Environmental Monitoring and Support Laboratory
Las Vegas, Nevada 89114

13. TYPE OF REPORT AND PERIOD COVERED
Final Contract Report

14. SPONSORING AGENCY CODE
EPA/600/07

15. SUPPLEMENTARY NOTES

16. ABSTRACT

An effective environmental monitoring program must have a quality assurance component to assure the production of valid data. Quality assurance has many components: calibration standards, standard reference materials, standard reference methods, interlaboratory comparison studies, and data validation. The purpose of this document is to identify and document the potential radioactive pollutants that could result from the expanded energy program and for which quality assurance programs must be provided.

The radionuclide releases and the resulting population exposure doses from several energy systems for four projected energy utilization scenarios were calculated and compared. The energy system components examined were: coal mining, processing, combustion, and ash disposal; coal gasification and liquefaction; oil shale mining, processing, residue disposal and product utilization; geothermal and development and operations; uranium mining, milling, conversion, enrichment and fabrication; nuclear reactor operations; and fuel reprocessing and waste disposal.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
coal oil shale geothermal nuclear systems radiation exposures radiation dosage	alternative energy programs energy systems human exposure calculation radioactive pollutants radiological projections	08 G,I 18 F,H 20 H

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED	21. NO. OF PAGES 142
	20. SECURITY CLASS (This page) UNCLASSIFIED	22. PRICE A07- A01

EPA-600/7-77-082
August 1977

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FOREWORD

Protection of the environment requires effective regulatory actions which are based on sound technical and scientific information. This information must include the quantitative description and linking of pollutant sources, transport mechanisms, interactions, and resulting effects on man and his environment. Because of the complexities involved, assessment of specific pollutants in the environment requires a total systems approach which transcends the media of air, water, and land. The Environmental Monitoring and Support Laboratory-Las Vegas contributes to the formation and enhancement of a sound integrated monitoring data base through multidisciplinary, multimedia programs designed to:

- develop and optimize systems and strategies for monitoring pollutants and their impact on the environment
- demonstrate new monitoring systems and technologies by applying them to fulfill special monitoring needs of the Agency's operating programs.

This report, "Potential Radioactive Pollutants Resulting from Expanded Energy Programs," will assist the EPA's quality assurance program in directing its efforts to meet the needs of laboratories engaged in monitoring radioactive pollutants or potential pollutants resulting from the expanded energy programs. The data contained in this report should be of value to those agencies involved in standard setting for energy development activities and for those monitoring the pollutants associated with these developments. For further information on this subject, contact the Quality Assurance Branch, Environmental Monitoring and Support Laboratory-Las Vegas, Nevada.

George B. Morgan

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Director
Environmental Monitoring and Support Laboratory
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SUMMARY

The radionuclide releases and the resulting population exposure doses from several energy systems for four projected energy utilization scenarios were calculated and compared. The energy system components examined were: coal mining, processing, combustion, and ash disposal; coal gasification and liquefaction; oil shale mining, processing, residue disposal and product utilization; geothermal development and operations; uranium mining, milling, conversion, enrichment and fabrication; nuclear reactor operations; and fuel reprocessing and waste disposal. The energy utilization scenarios included one that projected a high level of synthetic fuel production, one that projected high electrical power utilization--mostly derived from nuclear power developments beyond 1985, and one that assumes moderate developments in all energy systems along with energy conservation measures.

For nonnuclear energy systems, the dominant radionuclide contributing to population exposure doses is radon-222. The major sources of radon-222 releases are the coal ash piles created from the combustion of coal to produce electricity. On a per unit energy basis, the geothermal energy system is a comparable contributor to radon-222 exposure doses. Exposure doses derived from other radionuclides and from other nonnuclear energy systems are comparatively insignificant.

For nuclear energy systems, the radionuclides contributing to population exposure doses are ranked as follows: 1) tritium, 2) uranium-238, 3) radon-222, 4) krypton-85, 5) ruthenium-106, 6) xenon-133, 7) iodine-131 and iodine-129, 8) actinides, and 9) other fission and activation products. The sources of tritium population exposure doses are tritium releases to the environment from spent fuel reprocessing operations and from nuclear reactor operations. The uranium-238 releases, mostly during milling operations, also contribute to relatively significant population exposure doses. The population exposure doses derived from radon-222 releases from uranium mine and mill sites, however, are about the same order of magnitude as that derived from the release of radon-222 from coal ash piles.

There were wide differences in the data, both estimated and measured, on radionuclide release rates from nuclear energy system component operations and facilities, and the data on radioactive material releases from nonnuclear energy systems operations and facilities are extremely sparse and fragmented. Without more and better data, only order of magnitude estimates could be made on the effects of radionuclide releases from the various energy systems. Many assumptions, especially concerning the exposed population size, were necessary for the comparisons. These assumptions should be carefully considered in assessing the results.

1 INTRODUCTION

The Quality Assurance Branch of the U.S. Environmental Protection Agency's Environmental Monitoring and Support Laboratory-Las Vegas is responsible for providing an effective radiological quality assurance program for the Agency's energy program. A prerequisite for such a program is the identification and documentation of the important potential radioactive pollutants that could result from a program of energy expansion. Although proposed programs to develop domestic energy sources include the development of a variety of sources, near-term interest has focused on the development of geological resources such as the mining and use of western coal, mining and processing of oil shale, expansion of nuclear energy programs, and development of geothermal energy. The development of these geological resources--coal, oil shale, uranium, and geothermal energy--will increase the release of radioactivity to the environment. For example, open pit mining will continuously expose new layers of radioactivity-bearing materials to the elements, processing and use of the minerals will inject the radioactive contents into the environment, and fissioning of nuclear fuels will generate massive quantities of radioactive fission products. In the past, the lack of understanding of the hazards of radioactive materials has resulted in tragic and costly errors in the handling, use, and disposal of radioactive materials. Examples are the inhalation of radon by uranium miners, the ingestion of radium by watch dial painters, and the creation of hazardous uranium mill tailings piles.

It is the recognition of these and other past errors that prompted the current work to identify, analyze, and document the important potential radioactive pollutants resulting from a program of energy expansion so that measures can be taken to forestall possible unsafe radiological practices and unacceptable radiological contamination of the environment that might otherwise evolve. The results of the study must be considered preliminary, however. In the absence of detailed development plans, many assumptions concerning exposure pathways and exposed populations were necessary.

The radiological aspects of several energy systems are reported here. They include: coal mining, processing, combustion, and ash disposal; coal gasification and liquefaction; oil shale mining, processing, residue disposal, and product utilization; geothermal development and operations; and nuclear systems. The nuclear system components and operations covered include uranium mining and milling; uranium conversion, enrichment, and fuel fabrication; light water, high-temperature gas, and breeder reactors; and fuel reprocessing and waste disposal. Because high-temperature gas reactors and breeder reactors are still in the development stage and high level nuclear waste management remains unresolved, coverage of these subject areas is cursory.

In this report, proposed alternatives to expanded energy programs to meet projected U.S. energy demands through the end of the century are discussed, and four of six energy scenarios were selected for assessing the radiological effects of expanded energy development. This is followed by discussions on radionuclides of possible concern, their sources, means of release to the environment, pathways to human exposure, and the calculative methods used to convert projected release rates to population exposure doses for the purpose of ranking the relative importance of the radionuclide releases.

Next, the energy systems, resources, and system components are discussed, along with the radiological aspects associated with the energy systems, resources, and system components. Basic radionuclide content and release data are also presented. Using these basic release data and the projected energy utilizations by type, the radionuclide releases for 1985 and 2000 are then calculated and presented. The presentation of these releases in terms of population exposure doses follows. The final section is a discussion of the results.

II ALTERNATIVE EXPANDED ENERGY PROGRAMS

A. Background

Subsequent to the Arab oil embargo of 1973-74, the United States began to reevaluate its energy policies with the goals of reducing the impact of possible future embargoes in the near term and achieving a state of energy self-sufficiency in the long term. The main thrust of the programs formulated to achieve the goal of energy self-sufficiency was a significant expansion in the rate of exploitation of domestic energy resources to meet an energy demand that was expected to double by the year 2000. In addition, it was realized that the rate of growth in energy demand could be moderated if waste in energy consumption were reduced and some energy conservation efforts were begun.

To meet projected U.S. energy demands through the end of the century using domestic energy resources, it will be necessary to rely heavily on those resources with large reserves that have been relatively underused in the past. Although reliance on traditional sources of natural gas and crude oil, which together contribute over 75% of current energy supplies, will continue to be heavy, the production of these resources peaked in the early 1970s and will probably continue to decline to the end of the century. Some temporary increases in production will occur as Alaskan oil and other newly discovered reserves are brought into production, but these will serve mainly to offset the declining production from existing fields. Thus, it will be necessary to turn to the more abundant reserves of coal, oil shale, and uranium to meet growing energy demand. These sources will be supplemented by geothermal, solar, and other renewable energy sources.

The greatly expanded production of these energy sources will have widespread economic, social, and environmental impacts. The assessment of these impacts, including the effects of increased emissions of radionuclides, requires some quantitative estimate of the rate at which each energy resource will be exploited. Although no one can predict the future with certainty, there have been a number of projections of energy supply levels out to the year 2000. These projections are based on past trends, economics of supply and demand, likely technological developments, and quantities of energy resources in place. These projections can be used as a basis to quantify the possible impacts of future energy development.

B. U.S. Energy Supply Scenarios

A number of different groups have made energy supply and demand projections for the years 1985 to 2000. Each of these projections is based on an explicit set of assumptions about energy economics and technology, and each involves many uncertainties about the future energy picture, both domestic and international. For the purposes of the analysis to be done here, it is desirable to have a set of scenarios that bracket the nation's possible energy futures. Such a set should consider the range of technological options that may become available, and the effect of the various energy policy options that the nation may decide to carry out. The set of scenarios proposed by the U.S. Energy Research and Development Administration (ERDA) in its document ERDA-48, *A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future*, adequately fulfills these criteria. (Ref. 1)

The six energy scenarios developed in ERDA-48 provide a wide range of possible energy futures, emphasizing different technology options. Two of the scenarios--Scenario 0, No New Initiatives, and Scenario I, Improved Efficiencies in End Use--were judged to be of limited interest in terms of assessing the radiological effects of expanded energy development. The other four scenarios are discussed briefly below.

Scenario II--Synthetics from Coal and Shale

The dominant feature of this scenario is a high level of production of synthetic fuels from coal and oil shale, and its goal is a reduction in the high levels of imported petroleum that would otherwise be required to sustain a growing demand for liquid fuels. Additional energy supplies are provided through the enhanced recovery of oil and gas, and through nuclear power, continuing to grow at something like its historical rate. In this scenario, the contribution of geothermal energy remains relatively small. The projected growth of various energy supplies as a function of time is shown in Figure 1.

Scenario III--Intensive Electrification

In this scenario the emphasis is on the maximum utilization of electric power. The widespread introduction of electric cars is assumed along with increased efficiency in other uses of electricity. On the production side, the use of coal for electric power production is favored over conversion to synthetics. Greater use of nuclear power, including breeders, is projected, combined with faster development of geothermal, solar, and other alternative sources. This scenario is depicted in Figure 2.

Scenario IV--Limited Nuclear Power

In this scenario, it is assumed that for one reason or another (such as a nationwide nuclear moratorium) the level of nuclear power development is limited to those plants already built or on order. The difference between this low

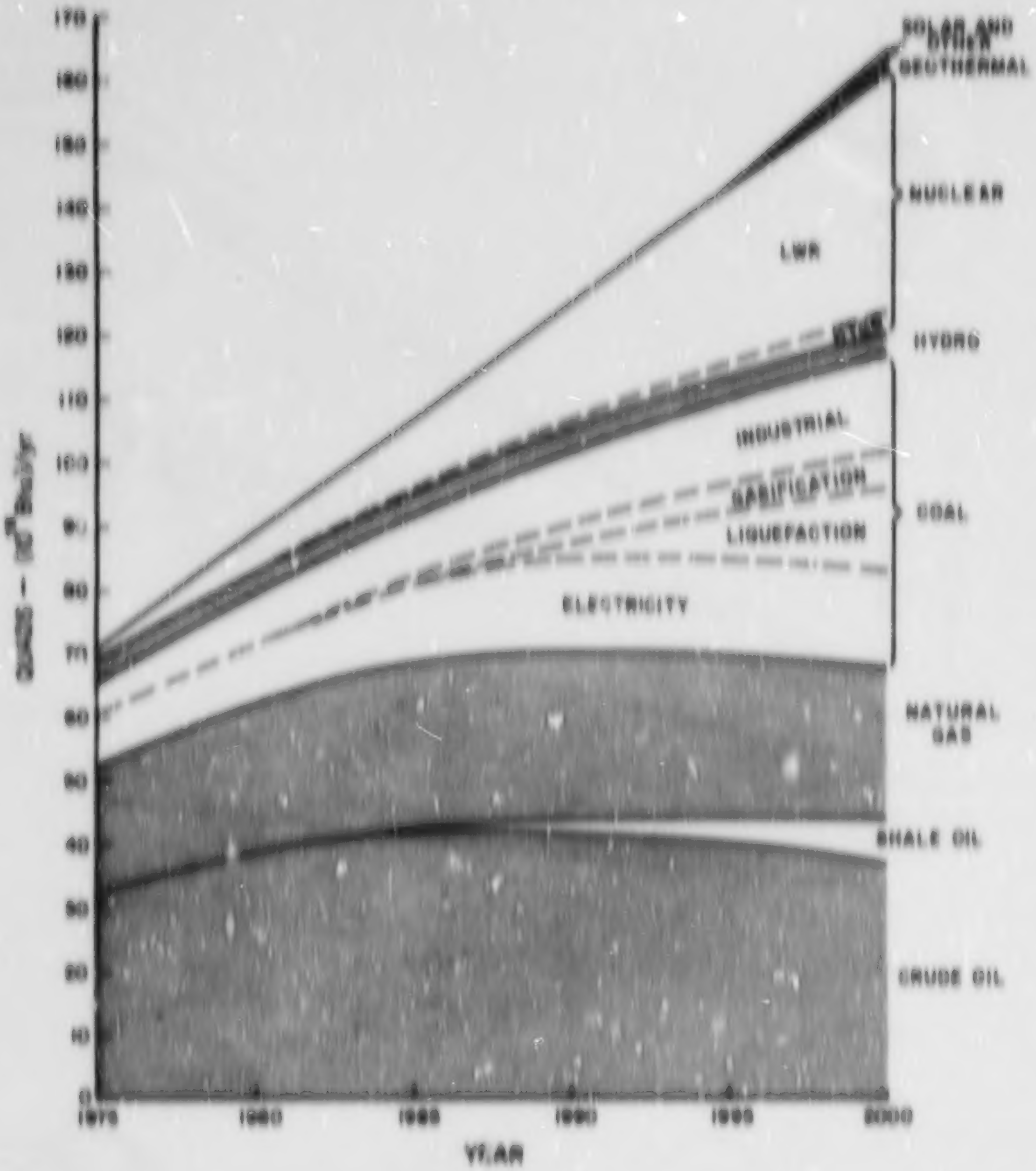

FIGURE 1. ERDA-48 SCENARIO II, SYNTHETICS FROM COAL AND SHALE

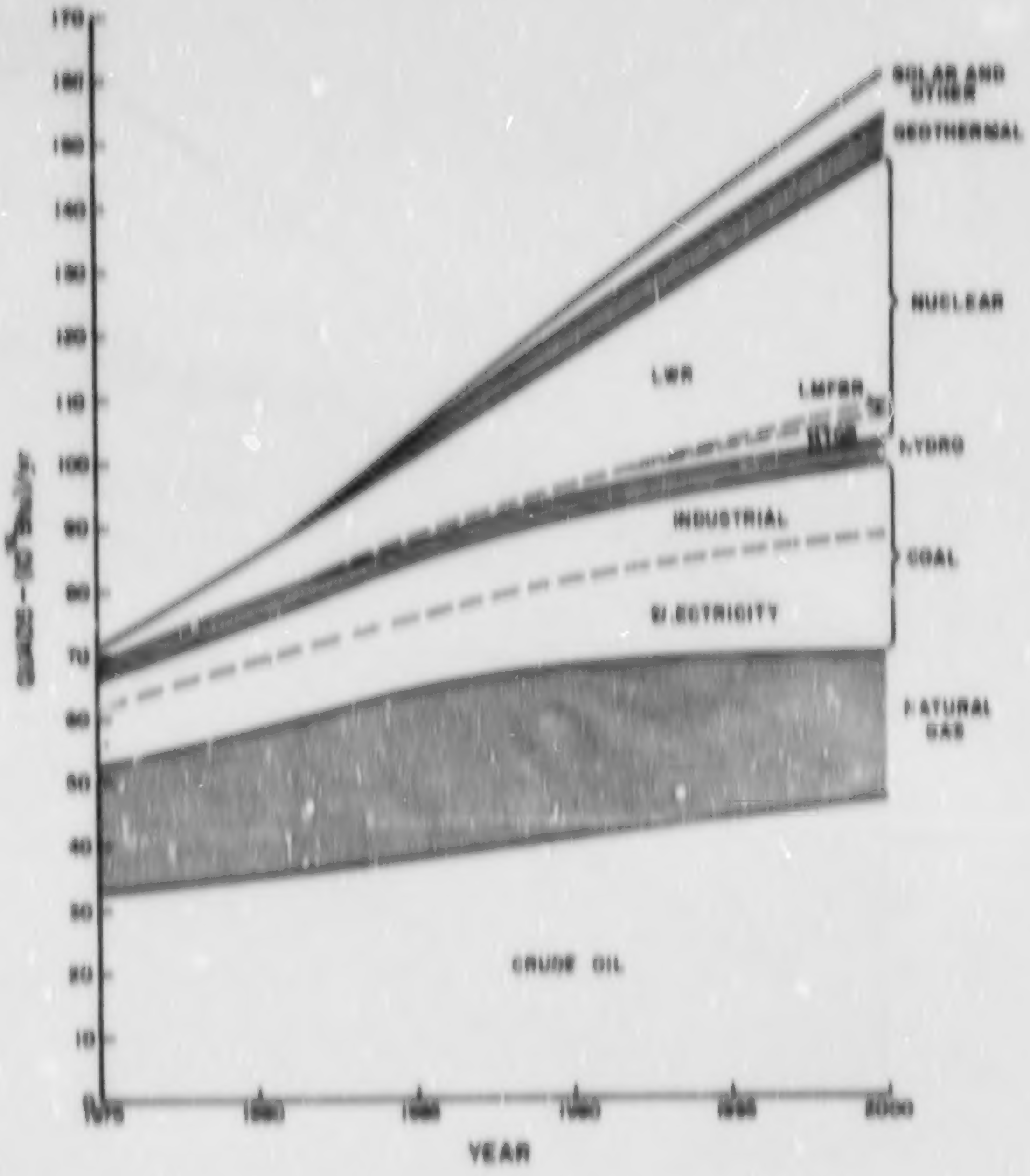

FIGURE 2. ERDA-48 SCENARIO III, INTENSIVE ELECTRIFICATION

level of nuclear power and the higher level projected in other scenarios is largely made up by accelerating geothermal and solar development at a rate even greater than in Scenario III. The total level of coal production is about the same as for Scenario III, including the same levels of synthetic fuel production. This scenario is depicted in Figure 3.

Scenario V—Combination of All Technologies

This scenario assumes a moderately high level of development of all the technologies considered in Scenarios II through IV, combined with an end-use conservation strategy that reduces energy demand by about 8% in 1985 and 13% in 2000. The result of this scenario is an elimination of petroleum imports by the end of the century. The main effect of end-use conservation is a reduction in demand for electricity that results in the use of coal and nuclear fuel for electricity production being reduced significantly below the levels of Scenarios II and III. This scenario is depicted in Figure 4.

C. Summary of Scenarios

The ERDA-48 Scenarios II through V are summarized in Table 1 and compared with 1975 data for the categories of energy supply considered in this study. Resource energy in the table is given in units of quads—10^{15} British thermal units (Btu).* As can be seen from the table, the four scenarios delineate a wide range of future resource consumption levels.

In the year 2000, the use of coal ranges over a factor of 1.6, geothermal over a factor of 10, and nuclear over a factor of 4. The use of coal and oil shale resources for the production of synthetic fuels ranges from 0 to 29 quads in the year 2000. In the nearer term (1985) the levels of resource use are not nearly as sensitive to the assumptions of the various scenarios, except in the case of geothermal which varies by a factor of 5 between Scenario II and Scenario IV.

All the scenarios show significant future increases in the use of coal, nuclear power, and geothermal energy compared with present levels, and significant levels of production of synthetic fuels (except Scenario III) compared to total gaseous and liquid-fuel use. These scenarios, thus, provide good frames of reference within which to assess the impact of radiological pollutants from an expanded energy program.

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*One Btu equals 1055 joules, so a quad is approximately 10^{18} joules.

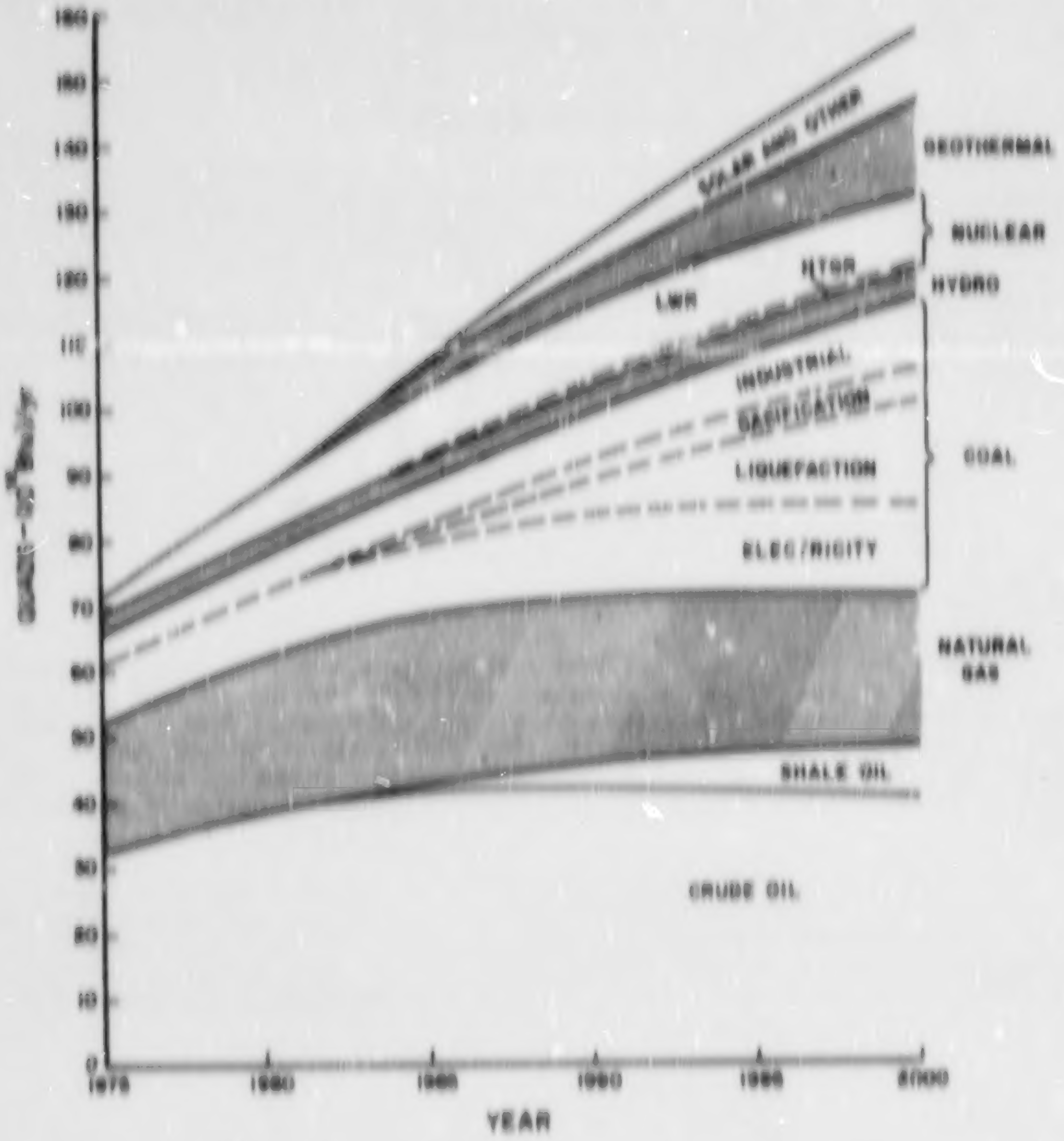

FIGURE 5. ERDA-48 SCENARIO IV, LIMITED NUCLEAR POWER

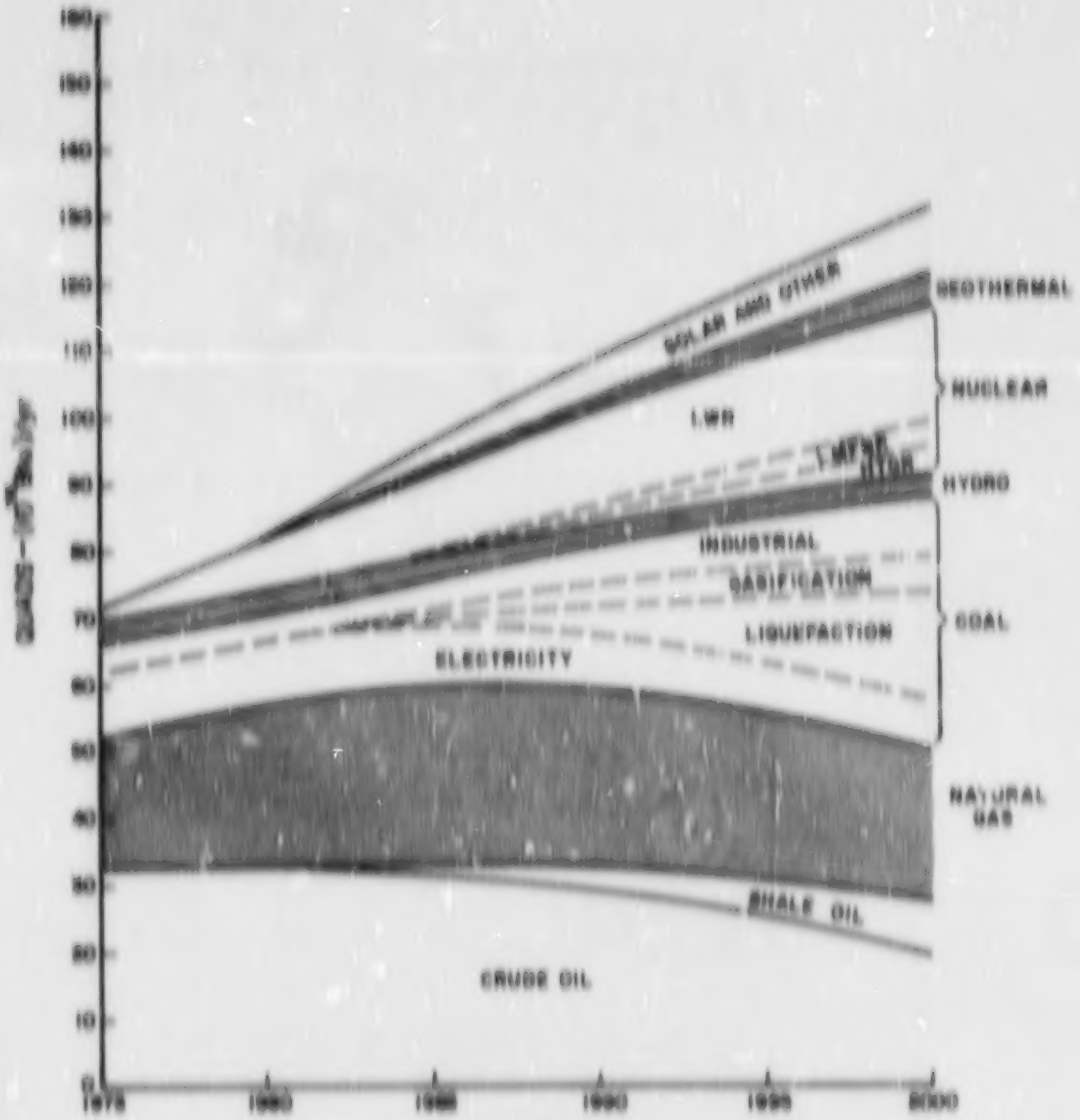

FIGURE 4. ERDA-48 SCENARIO V, COMBINATION OF ALL TECHNOLOGIES

TABLE 1. LEVELS OF ENERGY RESOURCE USE IN ERDA-48 SCENARIOS
(10^{15} Btu/year)

	Scenarios								
	II		III		IV		V		
Resource	1985	2000	1985	2000	1985	2000	1985	2000	1975*
Coal	23.28	44.77	20.10	30.51	19.90	45.07	18.13	39.11	15.5
Strip	11.64	20.90	10.05	12.81	9.96	19.27	9.06	16.43	8.40
Underground	11.64	20.87	10.05	17.70	9.99	25.60	9.07	22.60	7.10
Cleaned	19.64	27.06	18.60	29.06	16.33	23.26	14.40	16.40	7.60
Liquefied	0.73	15.91	–	–	0.73	15.81	0.73	15.81	–
Gasified	1.42	5.30	–	–	1.42	5.30	1.42	5.30	–
Electricity	12.51	15.21	12.51	18.38	11.43	13.71	9.51	8.43	8.82
Coke	2.81	3.54	2.81	3.54	2.58	2.83	2.59	2.34	2.40
Heat	3.49	4.90	2.48	3.60	1.58	3.83	1.71	3.14	2.06
Chemical	0.24	2.60	0.24	2.60	0.25	2.30	0.24	2.00	0.11
Oil shale	1.00	8.00	–	–	1.00	6.00	1.00	8.00	–
Geothermal	0.69	1.40	1.60	6.60	3.20	14.93	1.60	6.60	0.06
Electricity	0.69	1.40	1.40	5.60	3.00	13.93	1.40	5.60	0.06
Heat	–	–	0.20	1.00	0.20	1.00	0.20	1.00	–
Nuclear	10.85	40.49	13.21	44.39	10.85	11.37	13.21	34.30	1.65
LWR	10.61	36.59	12.97	36.61	10.60	10.97	12.97	26.50	1.65
HTGR	0.24	3.90	0.24	3.90	0.25	0.40	0.25	3.90	–
LMFBR	–	–	–	3.88	–	–	–	3.90	–

---

*Data for 1975 are from References 2, 3, 4, 5.

III RADIATION EXPOSURES

A. Radionuclides and Sources

The energy-related radionuclides considered in this report can be divided into three general categories:

(1) The *natural* light and heavy parent radionuclides (thorium and uranium), which occur significantly in nature

(2) The radioactive daughter products of the above heavy radionuclides

(3) Fission and transmutation products.

Table 2 presents the radionuclides of category (1), the *natural* light and heavy parent radionuclides. Natural tritium and carbon-14 are continuously produced from cosmic ray interactions in the upper atmosphere; the remaining natural radionuclides in Table 2 are primarily of terrestrial origin. Eisenbud (Ref. 6) lists several more singly occurring natural radionuclides; however, the above are estimated to be the most significant for energy emission considerations.

Thorium and uranium are the naturally occurring heavy radionuclides that decay into various daughters that are, in turn, ubiquitous in nature. The daughters can be assumed to be in secular equilibrium with the parent, which occurs when the half-life of the parent is *much* longer than that of the daughters. In secular equilibrium the activity of the daughters is roughly equal to that of the parent. Thus, in any natural deposits of thorium-232, uranium-235, and uranium-238 one would assume that the daughters' radioactivity is the same as the major parent. These three series of radioactive heavy elements are all found in the earth's crust or atmosphere and account for much of the radiation to which man is exposed.

The third category, fission and activation products, results primarily from neutron reactions. Products can be fission fragments of fissile isotopes and activation products of structural or coolant material and fuel materials.

State-of-the-art nuclear systems primarily revolve around uranium-235, which is a readily fissile isotope. Fission generally occurs when elements of heavy mass possess characteristic cross sections for thermal or fast neutron absorption, and liberate the absorbed excess energy by splitting into two smaller elements and neutrons. The average number of neutron products, as well as the fission yields of fragments, vary with energy of the absorbed neutron.

TABLE [illegible]. NATURAL LIGHT AND HEAVY SOURCE RADIONUCLIDES THAT OCCUR SIGNIFICANTLY IN NATURE[a]

Radionuclide	Half-Life (years)	Principal Radiations		Elemental Abundance (%)
		Energy (MeV)	Type	
Tritium	12.3	0.0186	β^-	
Carbon-14	5730	0.156	β^-	
Potassium-40	$1.26\text{x}10^9$	1.33 (89%) 1.46 (11%)	β^- γ (EC)	0.012
Vanadium-50	$6\text{x}10^{15}$	0.78 (30%) 1.55 (70%)	β^- γ (EC)	0.25
Rubidium-87	$4.8\text{x}10^{10}$	0.28	β^-	27.9
Lanthanum-138	$1.12\text{x}10^{11}$	0.21 0.81 1.43	β^- (80%) γ (EC) (70%) γ (EC)	0.09
Neodymium-144	$2.4\text{x}10^{15}$	1.83	α	23.0
Samarium-147	$1.05\text{x}10^{11}$	2.23	α	15.1
Lutetium-176	$2.2\text{x}10^{10}$	0.43	β^-	2.6
Thorium-232	$1.41\text{x}10^{10}$	3.95 (24%) 4.01 (76%)	α α	100
Uranium-238	$4.51\text{x}10^9$	4.15 (25%) 4.20 (75%)	α α	99.28
Uranium-235	$7.1\text{x}10^8$	4.37 (18%) 4.40 (57%) 4.58 (8%) 0.143 (11%) 0.185 (54%) 0.204 (5%)	α α α γ γ γ	0.72

---

[a]From Ref. 6.

Activation products resulting from neutron absorption (activation) in reactor material and actinides resulting from neutron capture by the heavy fuels material are also found in the spent fuel elements of nuclear reactors. For example, equations (1) and (2) show the production of plutonium-239 from the conversion of uranium-238.

$$^{238}U + {}^{1}n \rightarrow {}^{239}U^{*} \rightarrow {}^{239}Np + e^{-} \qquad (1)$$

$$^{239}Np \rightarrow {}^{239}Pu + e^{-} \qquad (2)$$

This is the basis of the breeder reactor operation whereby converted uranium-238 (as plutonium-239) is recycled as a mixed oxide with uranium. Table 3 lists some of the more important radioactive fission and activation products. These products were selected from various publications [Ref. 7, 9, 49], and all have environmentally significant half-lives.

B. Exposure Pathways and Health Effects

Exposure to radioactivity can result from both external and internal processes. Based on animal and epidemiological studies, the chronic health effects include cancer induction and mutagenic effects (somatic and genetic).

1. Exposure Pathways

HERMES is a comprehensive radiological exposure pathway model that is used to calculate regional dose commitments from nuclear reactors and reprocessing facilities. (Ref. 7) This Dose Calculation Model computes the exposure doses for air and water sources that flow through various ecological pathways to expose man either externally or internally. Table 4 presents the dose modes for internal and external exposures.

Experience has indicated that certain radionuclides and pathways are much more critical than others. Generally, for a specific radionuclide a few pathways will dominate. Likewise, for a specific component of a fuel's cycle, a singular mode of exposure will dominate. What is important in assessing the critical pathways is a knowledge of the recipient-to-donor concentration ratio throughout the model.

Dose assessment is a complex task and involves demography and habits, intermedia transport models, food chain dose factoring, source-emission factoring, internal metabolism, and route of entry of specific radionuclides. These can be divided into specific pathways for specific nuclides or fuel cycle components. Table 5 presents an example of critical pathways for specific nuclear reactor effluents. To present and utilize complex computational models for ranking is beyond the scope of this report. Therefore, simplified methods are presented.

TABLE 3. REACTOR FISSION AND ACTIVATION PRODUCTS

Fission Products	Activation Products
Tritium	Tritium
Krypton-85	Nitrogen-13
Krypton-85m	Carbon-14
Krypton-88	Sodium-22
Strontium-89	Sodium-24
Strontium-90	Argon-39
Yttrium-91	Argon-40
Zirconium-93	Calcium-41
Zirconium-95	Manganese-54
Niobium-95	Iron-55
Molybdenum-95	Iron-59
Molybdenum-99	Cobalt-58
Tellurium-99	Cobalt-60
Ruthenium-103	Nickel-63
Ruthenium-106	Copper-64
Antimony-125	Zinc-65
Tellurium-127m	Zirconium-95
Tellurium-129m	Niobium-95
Tellurium-132	Molybdenum-99
Iodine-129	Uranium-235
Iodine-131	Uranium-236
Iodine-132	Uranium-237
Iodine-133	Uranium-238
Iodine-135	Uranium-239
Xenon-131m	Neptunium-237
Xenon-133m	Plutonium-238
Xenon-133	Plutonium-239
Xenon-135m	Plutonium-240
Xenon-135	Plutonium-241
Xenon-138	Plutonium-242
Cesium-134	Plutonium-243
Cesium-135	Americium-241
Cesium-137	Americium-242m
Barium-140	Americium-242
Lanthanum-140	Americium-243
Cerium-141	Americium-244
Cerium-144	Curium-242
Promethium-147	Curium-243
Europium-155	Curium-244

TABLE 4. MODES OF HUMAN EXPOSURE

External Dose	Internal Dose
Air submersion	*Air Pathway*
Transpiration	Transpiration (tritium)
Soil exposure	Inhalation
River bank exposure	*Water Pathway*
Water immersion	Water consumption
Water surface exposure	Fish consumption
Irrigated fields	Water fowl consumption
	Food Pathway
	Vegetables (crops)
	Meat
	Milk
	Dairy foods
	Eggs

2. Liquid Effluent Releases and Dose Computation Methodology

Once an emission factor has been determined for a specific radionuclide, the dose received by a human or a population from water emissions can be computed by considering stream dilution, aquatic biota concentration, radioactive decay, and human water and aquatic biota consumption habits. Because we are only concerned about ranking various radionuclides, and not the actual computation of dose, the following static model given as equation 3 [Ref. 9] can be used to compare aquatic effluents:

$$D_w = \frac{Q}{M} \cdot e^{-\lambda t_i} \sum_{i}^{n} P\ DF$$

where D_w = water dose for radionuclide, μCi/yr

Q = release, μCi/yr

M = mass flow of receiving waters, cm³/yr

TABLE 5. PRINCIPAL EXPOSURE PATHWAYS FOR RADIATION EXPOSURE FROM NUCLEAR REACTOR EFFLUENTS[a]

Radionuclide	Discharge Mode	Principal Exposure Pathways	Critical Organ
Radioiodine	Airborne	Ground deposition-external irradiation	Whole body
		Air inhalation	Thyroid gland
		Grass-cow-milk	Thyroid gland
		Leafy vegetables	Thyroid gland
	Water	Drinking water	Thyroid gland
		Fish consumption	Thyroid gland
		Shellfish	Thyroid gland
Tritium	Airborne	Air inhalation and transpiration	Whole body
		Submersion	Skin
	Water	Drinking water	Whole body
		Food consumption	Whole body
Noble gases	Airborne	External irradiation	Whole body and skin
Cesium	Airborne	Ground deposition-external irradiation	Whole body
		Grass-cow-milk	Whole body
		Grass-meat	Whole body
		Inhalation	Whole body
	Water	Sediments-external irradiation	Whole body
		Drinking water	Whole body
		Fish consumption	Whole body
Transition metals (iron, cobalt, nickel, zinc, manganese)	Water	Drinking water	Gastrointestinal tract
		Shellfish consumption	Gastrointestinal tract
		Fish consumption	Gastrointestinal tract
Direct radiation	—	External irradiation	Whole body

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[a] Reference 8.

t_i = time between consumption and emission, day

n = number of pathways

P = pathway transfer factor, cm^3/yr

DF = stream dilution factor upon entrance to pathway

λ = radionuclide decay constant, day^{-1}

There obviously are many pathways by which humans can become exposed; however, the two most important are the consumption of aquatic biota and water. Thus, the parameter P (pathway transfer factor) requires further definition.

For water: $P_w = I_w F$

For food: $P_f = R[CF\ I + CF_s I_s]$

where I_s = intake of shellfish, cm^3/yr

I = intake of fish, cm^3/yr

I_w = drinking water consumption rate, cm^3/yr

F = water treatment loss factor

R = food preparation loss factor

CF = fish concentration factor

CF_s = shellfish concentration factor

Thus, the overall water exposure dose eqution is:

$$D_w = \frac{Q}{M} [I_w F\ (DF)\ e^{-\lambda t_i} + R(DF)(e^{-\lambda t_i})(I\ CF + I_s CF_s)] \qquad (4)$$

The simple evaluation for ranking relative exposures between aquatic radionuclides would be the computation presented in equation 4, and would be a function of each of the radionuclide variables Q, F, DF, λ, R, CF_s, and CF.

Site-specific differences for various components of the fuel cycles would be M (receiving water stream flows), t_i = (time between emission and exposure), Q for each radionuclide, and other factors. Assuming unit streams, consumption habits, and elapsed times, equal comparisons can be made. The input values for a unit site might be: [Ref. 9]

$H = 2000\ \text{ft}^3/\text{s} = 1.78 \times 10^{15}\ \text{cm}^3/\text{yr}$

$I_w = 8 \times 10^5\ \text{cm}^3/\text{yr}$

$I = 1.2 \times 10^3\ \text{cm}^3/\text{yr}$

$I = 5.1 \times 10^3\ \text{cm}^3/\text{yr}$

$t_1 = 30$ days

3. Atmospheric Emissions and Computation Methodology

As in the case of water emissions, we are concerned with computing exposures for each specific radionuclide following atmospheric emissions. Such a computation would involve a dispersion factor, radionuclide decay, transpiration, deposition and fallout, terrestrial-biotic interactions resulting in a food-chain dose, and direct inhalational and external exposures. Thus, in computing exposures from air sources we need to take into account both atmospheric and ingestion processes.

Equation 5 is used to provide a Gaussian concentration profile in the vertical direction and a uniform concentration in horizontal directions due to fractional wind frequencies and stability classes in various sectors. [Ref. 9]

$$\frac{\chi}{Q'} = \frac{\Psi}{Q} = \left(\frac{2}{\pi}\right)^{1/2} \frac{\text{FWF}\ e^{-(h^2/2\sigma_z^2)}\ e^{-\lambda t}}{\bar{u}\sigma_z 2\pi r/n} \qquad (5)$$

where χ = ground level airborne concentration, Ci/m³

Ψ = time integrated ground level concentration-exposure, Ci-s/m³

Q' = source release rate, Ci/s

Q = time integrated release (i.e., total release/yr), Ci

FWF = fractional wind frequency in a sector

r = distance from the stack, meters (m)

n = number of sectors

$2\pi r/n$ = sector width at distance r, m

h = effective stack height, m

σ_z = standard deviation of the vertical distribution of an assumed Gaussian cloud, m

$\bar{u}$ = average wind speed in the sector, m/s

λ = decay constant of radionuclide, s^{-1}

and t = transit time to distance r from the stack ($t = r/\bar{u}$), s.

This model is the basis for HERMES where direct inhalation or transpiration doses can be computed by equation 6: [Ref. 9]

$$D = \frac{\chi}{Q'} Q \text{ (DCF)} \qquad (6)$$

where D = dose rate, mrem/yr

χ/Q' = atmospheric dispersion factor as computed above, s/m^3

Q = annual release rate, Ci/yr

DCF = an appropriate dose conversion factor for the radionuclide and exposure mode of interest, mrem-m^3/Ci-s

Further computations give fallout, bioconcentration factors, and so on, to compute the dose for each specific radionuclide. The above models are too complex for our purposes.

To rank atmospheric emissions we would need unit model sites and conditions for various components of the cycles. A macrocondition pertains to a condition of the earth as a whole (for long-lived and widely distributed radionuclides), whereas microconditions pertain to local conditions around the source (for short-lived and locally distributed emissions). Macromodels have been derived from worldwide fallout models to assess the impact of atmospheric nuclear testing. In our case, however, we are limited to more defined source emission patterns for various components of fuel cycles. Thus, at this stage, prior to any common algorithmic expression, it is necessary to define which radionuclides would be of importance in worldwide, quasi-equilibrium exposure situations. The long-lived fission and activation products that would be expected to have macrodistributions would be the gases tritium and krypton-85, and the volatile iodine-129. Carbon-14 would also be expected to have a significant macrodistribution.[Ref. 10]

Often overlooked in calculating exposures is the macroregional distribution of radon-222 progeny (→ lead-210 → polonium-210). Radon is the source factor emanating to the atmosphere from uranium (radium-226) terrestrial formations when they are disturbed. Radon emanates naturally from soils at the average crustal rate of 1.4 pCi/m^2-s [Ref. 11]; however, anthropogenic emissions can be much greater [Ref. 12]. Although there are generally four decay steps between radon-222 and lead-210, the half-lives of the intermediate radon-222 daughters are relatively short, thus lead-210 biochemistry and geochemistry govern exposure along media transition zones. A case in point is that smokers are burdened with greater concentrations of polonium-210 in both lungs and bones than nonsmokers, due to its deposition on the broad leaf tobacco plant [Ref. 13].

To perform an initial assessment of the magnitude of radon emanation from both anthropogenic activities (mining-waste disposal) and natural emanation, we should consider the macroscale aspect. Using the following equation based on the previously given natural emanation rate of radon, we calculate:

$$Q_n = \phi A$$

where Q_n = conterminous U.S. natural radon-222 emanation rate, (Ci/yr)

ϕ = 1.4 pCi/m^2-s

A = 9.4 × 10^{12} m^2 for the United States

Solving the equation for Q_n, we obtain:

Q_n = 4.13 × 10^8 Ci/yr

Thus, approximately 400 MCi of radon-222 per year are emitted naturally from the conterminous United States. In performing an initial assessment, this natural emission would have to be compared with anthropogenic emissions. Anthropogenic emissions would involve (1) the emanation of terrestrially entrained radon-222 from uranium-238 ores during mining activities, and (2) the residual emanation of radon-222 from its parent radium-226 in spent mill piles (see Section IV.E-2).

Table 6 presents a summary of the mode and dose of natural radioactive backgrounds in the United States. Because of radon-220's short half-life, its longer-lived daughters, lead-212 and bismuth-212, are essentially in equilibrium and will contribute to higher exposure doses than those listed for radon-220.

TABLE 6. SUMMARY OF DOSE EQUIVALENT RATES (MREM/YEAR) FROM VARIOUS RADIONUCLIDES COMPOSING THE NATURAL BACKGROUND RADIOACTIVITY IN THE UNITED STATES FOR EXTERNAL (E), AIRBORNE (A), AND INTERNAL (I) EXPOSURES[a]

Radionuclide	Mode of Exposure	Gonads	Lung	Bone Surfaces	Bone Marrow	Gastrointestinal Tract[b]
Carbon-14	I	0.7	0.7	0.8	0.7	0.7
Potassium-40	E	8	8	8	8	8
	I	19	19	15	15	19
Rubidium-87	I	0.3	0.3	0.6	0.6	0.3
Uranium series	E	6	6	6	6	6
Uranium-238 (Uranium-234)	I	0.8	0.8	4.8	0.9	0.8
	A	—	0.2	—	—	—
Radium-226	I	0.2	0.2	6.6	1.2	0.2
	A	—	0.2	—	—	—
Radon-222	I	0.4	0.4	0.4	0.4	0.4
	A	—	2[c]	—	—	—
Polonium-218 (polonium-214)	A	—	90[d]	—	—	—
Lead-210 (polonium-210)	I	6	3	26	4.8	3
	A	—	21	—	—	—
Thorium series	E	12	12	12	12	12
Thorium-232	I	0.0	0.0	0.7	0.1	0.0
Radium-228	I	0.3	0.3	8.8	1.6	0.3
Lead-212 (bismuth-212)	A	—	3	—	—	—
Radon-220	I	0.0	0.0	0.2	0.2	0.0

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[a] Reference 14.

[b] Dose equivalent rate to the gastrointestinal tract is considered to be the same as for soft tissue, with no allowance for irradiation by the gut contents.

[c] Dose equivalent rate to bronchial surfaces.

[d] Dose equivalent rate to the segmental bronchioles would be 450 mrem/year.

Macroregional dose calculations for atmospheric emissions can be mathematically expressed by equation 7. Although the source factor (Q) is for air, the dose may also be for ingestion due to terrestrial deposit and biological accumulation. This general equation can be used to assess the relative annual doses received from annual releases of various radionuclides. Cumulative dose summations would be required for each year's increase in Q.

$$A = Qe^{-\lambda t_i} f_i F_i C_i \tag{7}$$

where A = dose from water (oral) or air (respiration), μCi/yr

Q = release factor, μCi/yr

λ = decay constant for radionuclide, yr^{-1}

t_i = time between emission and consumption, yr

f_i = environmental dilution factor for exposure compartment i, yr/cm^3

F_i = concentration factor for exposure compartment i, dimensionless

C_i = consumption for exposure compartment i, cm^3/yr

For macroregional exposures, as previously addressed, we would require evaluations based upon media dilution factors for appropriate pathways. These factors are presented in Table 7 for tritium, carbon-14, krypton-85, iodine-129, and plutonium-239.

4. Local Dose

Local radionuclide air doses from common sources in various components of the fuel cycles are calculated from constant environmental exposure conditions. In this methodology a simple area or point source model is used to compute average annual concentrations 3 kilometers (km) from the source. For calculating deposition, the average fallout is computed under the assumption that 80% of nonvolatiles are deposited within 10 km of the plant (Ref. 15). Assuming a stack height of 100 m and wind speed of 3 m/s, the dry deposition velocity term V_d would be approximately

$$\frac{2\ cm/s}{x},$$

where x is the downwind distance.

Using the following equation, the downwind ground level concentration can be computed for various source strengths and downwind distances from an area source. Turner's (Ref. 16) approximation of the horizontal dispersion

TABLE 7. [illegible] EXPOSURE COMPUTATION VARIABLES

Radionuclide	τ (yr)	λ (yr^{-1})	Exposure Compartment	f_1 (yr/cm^3)	F_1	C_2 (cm^3/yr)
Tritium	1	0.056	Eastern U.S. rain water Transpiration	2.53×10^{-19} 2.53×10^{-19}	0.5 1	8×10^{5} 1.65×10^{5}
Carbon-14	20	1.2×10^{-4}	Hemisphere (inhalation) Biosphere (air + food)	2.51×10^{-25} 2.51×10^{-25}	1 1	7.3×10^{3} 1.5×10^{5}
Krypton-85	1	0.064	Northern hemisphere (immersion)	2.51×10^{-25}	1	*
Iodine-129	1	4.3×10^{-8}	Eastern U.S. land area (grass → cow → milk)	2.6×10^{-17} (yr/cm^2)	2.8 (cm^{-1})	2.5×10^{5}
Plutonium-239	100	2.8×10^{-5}	Eastern U.S. land area (inhalation from resuspension)	2.6×10^{-17} (yr/cm^2)	10^{-7} (cm^{-1})	7.3×10^{3}

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*Not applicable for immersion.

is used where σ_{yo} = s/4.3, and s represents the side of the square area of the source. A virtual distance can be found, x_y, which varies with stability. Virtual distance x_y is then added to actual distance x for determining σ_y. With the area source being ground level, the model can be adjusted to include the radioactive decay term:

$$\chi = \frac{Qe^{-\lambda t}}{\pi\sigma_y\sigma_z U} \qquad (8)$$

where χ = air concentration, µCi/m³

Q = source strength, µCi/s

λ = radioactive decay constant, s⁻¹

t = time between emission and exposure, s

U = average wind speed, m/s

σ_y, σ_z = vertical and horizontal diffusion coefficients, m

Assuming area sources of 4 hectares (200 m)², σ_{yo} = 46.5 m. Thus at Class D stability:

$$\chi/Q = 1.45 \times 10^{-5}e^{-\lambda t}$$

where the following values have been used:

x = 3000 m, x_y = 900 m, and σ_y = 170 m at $x + x_y$

U = 3 m/s

σ_z (3 km) = 43 m

From point sources, if we assume that the radionuclide is uniformly distributed within horizontal sectors, annual average downwind concentrations can be estimated by (Ref. 16)

$$\chi = \frac{2.03\ Q\ e^{-0.5(H/\sigma_z)^2}e^{-\lambda t}}{\sigma_z Ux}$$

where definitions are the same as above and

x = downwind distance, m

H = stack height, m

The model facility for the point source assumes Class E (thin overcast with 2-3 m/s winds) stability and would have:

$U = 3$ m/s

$H = 100$ m

$x = 3000$ m

$\sigma_z = 43$ m.

The χ/Q term thus reduces to $3.51 \times 10^{-7} e^{-\lambda t}$. The above calculation can also be used to evaluate the relative atmospheric concentrations for the various area and point source nuclides in local environments.

Food-chain transport is of considerable importance for certain radionuclide exposures, as well as resuspension factors for others. Thus, the above models can be used to calculate the exposures via adjustments for deposition into soil and plants.

Radioactivity deposited on the ground surface can be calculated [Ref. 8] by

$$W = \frac{\chi}{Q} Q' V_d$$

Where Q' is the annual release rate (μCi/yr), V_d is the deposition velocity (0.02m/s), and W is the deposition rate (μCi/m^2-yr). Thus, the depositions at 3 and 80 km are:

$$W_3 = 7.02 \times 10^{-9} e^{-\lambda t} Q$$

$$W_{80} = 7.02 \times 10^{-11} e^{-\lambda t} Q$$

With the appropriate bioconcentration or resuspension factors, W is the deposition function for exposure estimates between radionuclides. This dose computation would be the same as for equation (7) but expressed as:

$$A = W\, F_i C_i \qquad (10)$$

where the F_i routes could be resuspension, ground → plant → man, plant → cow → milk → man, and plant → man and C_i is the annual consumption of the product. The soil acts as a reservoir for the accumulated deposit, thus increasing dose over time. The deposit is lost from the system through percolation, resuspension, or wash-off, as well as the physical decay constant of a particular radionuclide. The accumulated deposit in $\mu Ci/m^2$ can be given as:

$$D = \frac{(\chi/Q)\, Q' V_d (1 - e^{-\lambda_e t})}{\lambda_e}$$

where λ_e = the sum of the removal rates for the various processes (i.e., $\lambda_a + \lambda_b + \cdots$), yr^{-1}, and the other terms are as previously defined.

The rationale in the above methodologies is the computation of constant human exposure concentrations for the principal pathway media, given Q's and environmental parameters. In estimating human dose, all modes must be taken into consideration to calculate actual exposures from all consumption; then, dose factors must be supplied for the critical organs of the exposed populations. These organ dose factors convert radioactivity per cm^3 of the exposure medium to dose (rem) per year. Thus, given a quantity of consumption per year, the annual critical organ dose can be computed. Within the limits of our calculations, it would be inaccurate and misleading to compute estimates of population dose for other than ranking purposes for the following reasons:

- The results may be erroneously taken to imply health effects
- Variable demographic patterns and habits have not been incorporated
- All exposure media have not been utilized
- There are variable source conditions that are beyond incorporation in these models
- Environmental transfer and concentration factors are, at best, order of magnitude estimates
- Our estimates and results appear conservative.

To estimate the organ dose, the calculations would be as follows:

$$D_{mj} = \chi_{ji} C_i F_{mj}$$

where D_{mj} = dose to organ m from radionuclide j, rem/yr

χ_{ji} = annual average concentration of radionuclide j in exposure mode i, $\mu Ci/cm^3$

C_i = consumption of exposure mode i, cm^3/yr

F_{mj} = the exposure mode dependent dose conversion factor for organ m and radionuclide j, rem/μCi

These organ dose conversion factors generally assume homogeneous distribution in organs. To obtain total dose to organs from specific sources all D_{mj}'s should be summed.

There are Federal regulations (10CFR20.1) on the maximum permissible concentrations of radionuclides allowed in effluents to unrestricted areas. The regulations for air and water are presented in 10CFR20, Appendix B, Table II.

A considerable amount of work has been done in the past on calculating limits for all of the radionuclides. The most comprehensive tabulations of the background, primarily for internal dose, are found in ICRP #2 (1959) or in Health Physics (1959) [Ref. 17].

The basic formula that is used to calculate organ dose (rem/yr) is:

$$D_m = \frac{1.86 \times 10^4 (B_m)(E)(Q.F.)}{G}$$

where D_m = dose, rem/yr

B_m = organ burden, µCi

E = energy per disintegration, MeV

$Q.F.$ = quality factor for radiation type

G = organ mass, g

The constant (1.86×10^4) is derived from the integral of the time period for energy (rad = 100 ergs/g) absorbed by the tissue per microcurie. The value (E) is highly dependent on the type of energy, its level, and the nature of the tissue. This value would hold constant if equilibrium existed in the organ. Because energy emissions per disintegration are constant, the product of (E) and (Q.F.) can be calculated for each organ of the body and radionuclide, as the effective energy (E'), where Q.F. varies with radiation type.

The maximum permissible body burden for each radionuclide is the maximum amount the body can take without delivering a dose exceeding the maximum permissible level (rem/yr) for a critical organ. The maximum permissible burdens are the object of continual research.

The EPA has proposed standards on Radiation Protection for Nuclear Power Operations (FR23432, 1975) limiting dose equivalent rates to the maximum permissible levels for the critical body organs in Table 8. This table also included proposed standards for the specific macrodistributed nuclides, krypton-85, iodine-129, and some actinides.

TABLE 8. PROPOSED RULES (FR23421, 1975)

(a)		(b)	
Organ	mrem/yr	Nuclides	Ci/GW-yr
Wholebody	25	Krypton-85	50,000
Thyroid	75	Iodine-129	0.005
Others	25	Long-lived actinides	0.0005

Maximum permissible body burdens can, thus, be translated to annual continuous exposures and to specific radionuclides or mixtures of radionuclides (the latter contribute to organ dose as a whole) given the fraction of the body burden that is present in the organ in question. This value, f_{mj}, is specific for each radionuclide and organ. For example, assuming the thyroid organ mass for a standard adult is 20 g, f_{mj} for iodine-129 is 0.25 and $E' = 0.046$, the value for the maximum permissible body burden, based on iodine-129 exposure of 75 mrem/yr to the thyroid, is

$$B = \frac{(0.075)(20)}{1.86 \times 10^{4}(0.046)(0.25)} = 7 \times 10^{-3}\ \mu Ci$$

and the burden in the thyroid is

$$B_m = f_{mj}B = 0.25 \times 7 \times 10^{-3} = 1.75 \times 10^{-3}\ \mu Ci$$

Table 9 presents the maximum permissible concentrations for air (MPCa) and water (MPCw) formulas for continuous exposures to air and water.

C. Human Exposure Calculation

MPCs will vary according to the specific radionuclides in question and to the conversion factors (rem/µCi) under consideration. As shown, the conversion factors will be a function of the maximum permissible organ concentration for a specific radionuclide based on health effects evaluations, its solubility and the fraction from air and water reaching the critical organ (f_a, f_w), and the radionuclide's effective half-life (T_E). For ranking purposes, the isotopes in Table 10 are considered, with MPC_a and MPC_w from 10CFR20, Appendix B, Table II. The minimum MPCs between soluble and insoluble forms is presented. Based upon the organ exposures presented in NBS Handbook #69 [Ref. 18], which generally show allowable continuous occupational exposures a factor of 10 higher than the current NRC regulations, dose conversion factors are calulated (rem per year/ μCi per year) for the critical organ and are presented in the right-hand columns. Some changes have been made in the table, most notably for radon-222, radium-226, uranium-235, and uranium-238. These changes were based on dose conversion factors presented in Ref. 8 and 9 concerning the nuclear fuel cycle. Modifications for radon-226, uranium-235, and uranium-238 should be used with considerable caution because of their more than ten-fold differences from the NBS data. For the latter, the MPCs were changed to correspond to 3 rem/yr for bone and 1.5 rem/yr for lung. Furthermore, the dose conversion factors were for the minimum MPC, soluble(s) or insoluble (i). Thus, the use of a given factor implicitly assumes that all of the nuclide is in either the i or s form.

TABLE 9. MAXIMUM PERMISSIBLE CONCENTRATION FORMULAS

MPC_{air} (μCi/cm³)	MPC_{water} (μCi/cm³)
$MPC_a = \dfrac{5 \times 10^{-8}(B)(f_m)}{f_a(T_E)(1-e^{-.693(50)/T_E})}$	$MPC_w = \dfrac{4.5 \times 10^{-5}(B)(f_m)}{f_w(T_E)(1-e^{-.693(50)/T_E})}$
Inhalation = 2×10^7 cm³/day	Water = 2200 cm³/day

B = body burden which will account for maximum critical organ exposure, μCi

f_m = fraction of body burden in critical organ

f_a, f_w = fraction of nuclide reaching critical organ

T_E = biological effective half-life, days, = $\dfrac{T_B T_R}{T_B + T_R}$

T_B = biological half-life, days

T_R = radiological half-life, days

(50) = 50 years in days = 1.8×10^4 days

Thus, for iodine-129, for which Bf_m was calculated at 1.75×10^{-3} μCi, and with $f_a = 0.23$, $f_w = 0.3$, $T_B = 138$, and $T_R = 6.2 \times 10^9$,

TABLE 10. MAXIMUM PERMISSIBLE CONCENTRATION

Radioisotopes	[µCi/cm^3]		Dose Conversion Factor [rem/µCi]*			
			Water		Air	
	MPC$_w$	MPC$_a$	Organ	Factor	Organ	Factor
Tritium	3×10^{-3}(s)[†]	2×10^{-7}(s)	Tissue	2.1×10^{-4}	Tissue	3.5×10^{-4}
Carbon-14	8×10^{-4}(s)	10^{-7}s	Fat	7.8×10^{-4}	Fat	6.8×10^{-4}
Potassium-40	7×10^{-6}(i)	1.5×10^{-9}(i)	GI	0.26	GI	0.14
Iron-59	5×10^{-5}(i)	2×10^{-8}(i)	GI	0.037	Lung	0.103
Krypton-85	—	3×10^{-7}	—	—	Total body	2.1×10^{-4}
Rubidium-87	10^{-4}(s)	2×10^{-9}(i)	Pancreas	0.019	Lung	0.1
Strontium-89	3×10^{-6}(s)	3×10^{-10}(i,s)	Bone	1.7	Bone	1.3
Strontium-90	3×10^{-7}(s)	3×10^{-11}(s)	Bone	12	Bone	13
Ruthenium-103	8×10^{-5}(i,s)	3×10^{-9}(i)	GI	0.02	Lung	0.07
Ruthenium-106	10^{-5} (i,s)	2×10^{-10}(i)	GI	0.19	Lung	1.08
Iodine-129	6×10^{-8}(s)	2×10^{-11}(s)	Thyroid	62.5	Thyroid	20.6
Iodine-131	3×10^{-7}(s)	1×10^{-10}(s)	Thyroid	12.5	Thyroid	4.1
Xenon-133m	—	4×10^{-7}	—	—	Total body	1.7×10^{-4}
Cesium-134	9×10^{-6}(s)	4×10^{-10}(i)	Total body	0.07	Lung	0.51
Cesium-137	2×10^{-5}(s)	5×10^{-10}(i)	Total body	0.103	Lung	0.41
Samarium-147	6×10^{-5}(s)	2×10^{-12}(s)	Bone	0.06	Bone	192
Lead-210	10^{-7}(s)	4×10^{-12}(s)	Kidney	16.7	Kidney	51.2
Radon-222	—	4×10^{-10}			Lung	0.54
Radium-226	2×10^{-7}(s)	1×10^{-12}(i)	Bone	26.4	Lung[‡]	1506
Thorium-232	2×10^{-6}(s)	10^{-12}(i,s)	Bone	1.8	Bone	383
Uranium-235	3×10^{-7}(s)	1×10^{-12}(i)	Bone	12.3	Lung	1428
Uranium-238	3×10^{-7}(s)	1×10^{-12}(s)	Bone	12.3	Lung	1428
Plutonium-238	5×10^{-6}(s)	7×10^{-14}(s)	Bone	0.7	Bone	5471
Plutonium-239	5×10^{-6}(s)	6×10^{-14}(s)	Bone	0.7	Bone	6383
Plutonium-240	5×10^{-6}(s)	6×10^{-14}(s)	Bone	0.7	Bone	6383
Plutonium-241	2×10^{-4}(s)	3×10^{-12}(s)	Bone	0.017	Bone	127
Polonium-210	7×10^{-7}(s)	7×10^{-12}(s)	spleen	2.7	Lung	29

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*For ranking purposes only.
[†] Soluble(s); Insoluble (i).
[‡] Assumed.

the proposed EPA regulations would be:

$$MPC_a = 2.7 \times 10^{-12}\ \mu Ci/cm^3 \text{ of air}$$

$$MPC_w = 1.9 \times 10^{-8}\ \mu Ci/cm^3 \text{ of water}$$

1. Water Dose

Table 11 presents the variables to be used in computing from equation 6 the water exposure dose for a man. Columns a, b, and c provide the dose (μCi/yr), organ, and exposure (rem/yr) to the critical organ when Q (μCi/yr) is substituted. On checking tritium results of Table 11 with Q data on page 130 of Ref. 9, the rem/year factor calculates Q5E-15,[a] a factor of approximately 1/20 of column (c)--tritium. This is surprising, in that almost all variables (including dilution) were similar. The dose conversion factor from Table 10 (2.1×10^{-4} rem/μCi) for tritium is probably excessive by a factor of 2, as is the water consumption parameter (2200 cm^3/day); however, this should only lead to a reduction of about one-fifth. Thus, the data should be used with caution and only for ranking purposes until parameters are firmly reevaluated and reasonably established with uncertainty estimates. Furthermore, this data should not be construed to imply health effects.

2. Atmospheric Dose

a. Macroregional

Table 12 presents the algorithms to be used in computing macroregional dose based on equation 7 and the variables presented in Table 7. This would apply primarily to the United States.

b. Area Source

The only significant radionuclide emitted from a broad area source would be radon-222. Equation 8 presents the area source calculation with a χ/Q of $1.45 \times 10^{-5}\ e^{-\lambda t}$ for a 4 hectare source. A 40-hectare source would have a reduction effect of about 0.4, and annual averages would have a reduction effect of 0.1 to 0.5. Thus, using a χ/Q of approximately $1.45 \times 10^{-6}\ e^{-\lambda t}$ ($\mu Ci/m^3$), the dose algorithms for radon-222 (inhalation) for a person continuously at 3 km would be

Exposure Dose (μCi/yr)	Organ Dose (rem/yr)
Q 3.4E-10	Q 1.8E-10

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[a] This notation (Q)5E-15) is equivalent to $Q \times 5 \times 10^{-15}$.

TABLE 11. WATER TRANSPORT DOSE VARIABLES AND Q-DOSE ALGORITHMS

Equation (4) Radionuclide Variable Values

Radioisotopes	λ(day^{-1})	DF	F	R	CF	CF$_s$	(a) Exposure Dose, D_E (μCi/yr)	(b) Organ	(c) Organ Dose, D_O (rem/yr)
Tritium	1.54×10^{-4}	1	1	0.8	1	1	Q4.5E-10	Tissue	Q9.4E-14
Carbon-14	3.31×10^{-7}	1	1	0.8	1	1	Q4.5E-10	Fat	Q3.5E-13
Potassium-40	1.4×10^{-12}	0.05	(0.5)*	0.8	(500)	(500)	Q8.2E-11	GI(I)†	Q2.1E-11
Iron-59	0.0154	0.05	0.2	0.8	1,000	20,000	Q8.2E-11	GI(I)	Q3E-10
Krypton-85	1.76×10^{-4}	0.05	—	0.8	—	—	Q1.1E-11		
Rubidium-87	4×10^{-14}	0.05	(0.2)	0.8	(50)	(50)	Q1.2E-11	Pancreas(s)	Q2E-13
Strontium-89	0.0133	0.05	(0.2)	0.8	50	500	Q1.6E-11	Bone(s)	Q2E-11
Strontium-90	6.7×10^{-5}	0.05	(0.2)	0.8	50	500	Q2.4E-11	Bone(s)	Q3E-10
Ruthenium-103	0.017	0.05	0.2	0.8	100	1000	Q2.6E-11	GI(I)	Q5E-13
Ruthenium-106	1.88×10^{-3}	0.05	0.2	0.8	100	1000	Q4.3E-11	GI(I)	Q6E-12
Iodine-129	1.1×10^{-10}	0.05	0.8	0.8	1	25	Q2.3E-11	Thyroid(s)	Q1E-9
Iodine-131	0.086	0.05	0.8	0.8	1	25	Q1.9E-12	Thyroid(s)	Q2E-11
Xenon-131m	0.131	0.05	—	0.8	—	—			
Cesium-134	9.2×10^{-4}	0.05	0.8	0.8	1000	1000	Q1.6E-10	Total body(s)	Q1E-11
Cesium-137	6.3×10^{-5}	0.05	0.8	0.8	1000	1000	Q1.6E-10	Total body(s)	Q5E-12
Samarium-147	1.7×10^{-14}	0.05	(0.2)	0.8	(50)	(50)	Q1.1E-11	Bone(s)	Q7E-13
Lead-210	9×10^{-5}	0.05	(0.2)	0.8	(50)	(50)	Q1.1E-11	Kidney(s)	Q2E-10
Radon-222	0.18	0.05	—	0.8	—	—			
Radium-226	1.2×10^{-6}	0.05	(0.2)	0.8	(10)	(10)	Q6E-12	Bone(s)	Q9E-11
Thorium-232	1.3×10^{-13}	0.05	(0.2)	0.8	(10)	(10)	Q6E-12	Bone(s)	Q1E-11
Uranium-235	2.7×10^{-12}	0.05	(0.2)	0.8	(10)	(10)	Q6E-12	Bone(s)	Q7E-11
Uranium-238	4.2×10^{-13}	0.05	(0.2)	0.8	(10)	(10)	Q6E-12	Bone(s)	Q7E-11
Plutonium-238	2.2×10^{-5}	0.05	(0.2)	0.8	(10)	(10)	Q6E-12	Bone(s)	Q4E-12
Plutonium-239	7.9×10^{-8}	0.05	(0.2)	0.8	(10)	(10)	Q6E-12	Bone(s)	Q4E-12
Plutonium-240	2.9×10^{-7}	0.05	(0.2)	0.8	(10)	(10)	Q6E-12	Bone(s)	Q4E-12
Plutonium-241	1.26×10^{-4}	0.05	(0.2)	0.8	(10)	(10)	Q6E-12	Bone(s)	Q1E-13
Polonium-210	5×10^{-3}	0.05	(0.5)	0.8	(10)	(10)	Q1.5E-11	Spleen(s)	Q4E-11

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*Estimates ( )

†Soluble (s); insoluble (I).

TABLE 12. MACROREGIONAL DOSE ALGORITHMS

Nuclide	Exposure Dose (μCi/yr)	Organ	Organ Dose (rem/yr)
Tritium	Q1E-13[a]	Tissue (water)	Q2E-17
	Q9E-14	Transpiration (air)	Q3E-17
			Q5E-17
Carbon-14	Q2E-15	Body fat	Q1.3E-18
Krypton-85	Q2E-25	External	Q5E-29
Plutonium-239	Q2E-14	Lung (i)[†] or Bone(s)	Q2E-11 Q1E-10

[a] Q1E-13 = Q x 1 x 10^{-13}

[†] Insoluble (i); soluble (s).

where Q is in μCi/yr emanating from the source. From the source, an additional factor of 10^{-4} can be used for computing concentrations out to 80 km; however, daughter build-up must be taken into consideration. In the above case, we have considered a dose at 3 km. At 3 m/sec it would take the effluent about 15 minutes, or 0.01 day, to travel 3 km. During this time, about 0.2% of the radon-222 activity would have decayed. At 3 km, the daughter, polonium-218, would have built up to 5.3 x 10^{-5} of the radon-222 activity, or at this point polonium-218 exposure would be Q1.2E-12 μCi/yr, where Q is in microcuries of radon-222 per year.

c. Point Source

Point source atmospheric emissions are presented in equation 9, which gives a χ/Q term of 3.5 x $10^{-7}e^{-\lambda t}$ out to 3 km for annual average concentrations. For average concentrations out to 80 km, a factor of approximately 10^{-4} should be applied.

As presented in equation 9, Q is in μCi/s, and χ is in μCi/m^3. Adjusting these terms for annual emissions (3.2 x 10^{-8} yr/s) and annual inhalation (7300 m^3/yr), the annual dose (μCi/yr) can be computed at 3 km. Depletion due to fallout has not been taken into consideration; thus, when extrapolating dose to 80 km, the results should be interpreted with caution as being conservative. For 3 km, the annual dose (μCi/yr) would be estimated by $8Qe^{-\lambda t}$E-11 and to 80 km approximately $8Qe^{-\lambda t}$E-15 where t is 0.01 day (3 km) and 0.31 day (80 km).

Table 13 presents the exposure dose and organ dose (rem/yr) for the radionuclides listed in Table 10.

3. Air-Food Dose

Equation 10 presents the air-food exposure pathway based on W (μCi/m^2-yr), the deposition factor, calculated for the model facility as $Q'7 \times 10^{-9} e^{-\lambda t}$ at 3 km. For up to 80 km, W is $Q'7 \times 10^{-11} e^{-\lambda t}$.

Exposure will be considered for four modes:

(a) Air→ground→plant→man

(b) air→plant→man

(c) air→plant→cow→milk→man

(d) air→ground→man

For mode (a), the deposit is assumed to uniformly mix in the top cm of the soil. Assuming a soil density of 2.7 g/cm^3, the soil mass density would be 135 kg/m^2. It is also assumed that the average adult consumes 30 kg of plants/year. Thus: process (a) reduces to:

$$F_{gp} Q' 1.6\ E{-}9\ e^{-\lambda t}\ \mu Ci/yr \qquad (a)$$

where t = 90 days between emission and plant consumption and F_{gp} = fraction in plant for unit ground deposit.

For mode (b), 0.25 of the deposit is retained by the plant, it is "weathered" away with a half-life of 12 days, and only a fraction remains in the portion ingested; more is lost during preparation (0.1). The expression for this process is:

$$Q' 2.9 \times 10^{-11} e^{-\lambda t}\ \mu Ci/yr \qquad (b)$$

For mode (c), 0.25 of the deposit is retained on the plant as above, 0.3 is lost by weathering before cow consumption, the cow forages 0.4 of the year on 36 m^2 per day, the radionuclide transfers to milk at a ratio B_4 (μCi/liter per μCi/day), and an adult consumes 84 liters milk per year. The expression for this process is:

$$B_4 Q' 6.3 \times 10^{-7} e^{-\lambda t}\ \mu Ci/yr \qquad (c)$$

TABLE 13. LOCAL ATMOSPHERIC EXPOSURE ALGORITHMS

Radioisotopes	λ(day^{-1})	Exposure Dose (μCi/yr) 3 km	Exposure Dose (μCi/yr) 80 km	Organ	Organ Dose (rem/yr) 3 km	Organ Dose (rem/yr) 80 km
Tritium	1.5×10^{-4}	9QE-11	9QE-15	Tissues(s)*	Q3E-14	Q3E-18
Carbon-14	3.3×10^{-7}	9QE-11	9QE-15	Fats(s)	Q5E-14	Q5E-18
Potassium-40	1.4×10^{-12}	9QE-11	9QE-15	GI(i)	QE-11	QE-15
Iron-59	0.0154	9QE-11	9QE-15	Lung(i)	Q8E-12	Q8E-16
Krypton-85	1.76×10^{-4}	9QE-11	9QE-15	Total body	Q2E-14	Q2E-18
Rubidium-87	4×10^{-14}	9QE-11	9QE-15	Lung(i)	Q9E-12	Q8E-16
Strontium-89	0.0133	9QE-11	9QE-15	Bone(i,s)	Q5-10	QE-14
Strontium-90	6.7×10^{-5}	9QE-11	9QE-15	Bone(s)	Q6-9	QE-13
Ruthenium-103	0.017	9QE-11	9QE-15	Lung(i)	Q5.6E-12	Q5.6E-16
Ruthenium-106	1.9×10^{-3}	9QE-11	9QE-15	Lung(i)	Q9E-11	Q9E-15
Iodine-129	1×10^{-10}	9QE-11	9QE-15	Thyroid(s)	Q1.6E-9	Q1.6E-13
Iodine-131	0.086	9QE-11	7.8QE-15	Thyroid(s)	Q3.3E-10	Q3.2E-14
Xenon-131m	0.131	9QE-11	7.7QE-15	Total body	Q1.4E-14	Q1.3E-18
Cesium-134	9.2×10^{-4}	9QE-11	9QE-15	Lung(i)	Q4E-11	Q4E-15
Cesium-137	6.3×10^{-5}	9QE-11	9QE-15	Lung(i)	Q3.3E-11	Q3.3E-15
Samarium-147	1.7×10^{-14}	9QE-11	9QE-15	Bone(s)	Q1.5E-8	Q1.5E-12
Lead-210	9×10^{-5}	9QE-11	9QE-15	Kidney(s)	Q4.1E-9	Q4.1E-13
Radon-222	0.18	9QE-11	7.5QE-15	Lung	Q4.0E-11	Q3.7E-15
Radium-226	1.2×10^{-6}	9QE-11	7.5QE-15	Lung(i)	Q1.2E-7	Q1.2E-11
Thorium-232	1.3×10^{-13}	9QE-11	7.5QE-15	Bone(i,s)	Q3.1E-8	Q3.1E-12
Uranium-235	2.7×10^{-12}	9QE-11	7.5QE-15	Lung(i)	Q1.1E-7	Q1.1E-11
Uranium-238	4.2×10^{-13}	9QE-11	7.5QE-15	Lung(i)	Q1.1E-7	Q1.1E-11
Plutonium-238	2.2×10^{-5}	9QE-11	7.5QE-15	Bone(s)	Q4.4E-7	Q4.4E-11
Plutonium-239	7.9×10^{-8}	9QE-11	7.5QE-15	Bone(s)	Q5.1E-7	Q5.1E-11
Plutonium-240	2.9×10^{-7}	9QE-11	7.5QE-15	Bone(s)	Q5.1E-7	Q5.1E-11
Plutonium-241	1.3×10^{-4}	9QE-11	7.5QE-15	Bone(s)	Q1.0E-8	Q1.0E-12
Polonium-210	5×10^{-3}	9QE-11	7.5QE-15	Lung(i)	Q2.3E-9	Q2.3E-13

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*Soluble (s); insoluble (i).

For mode (d), the resuspension factor is $F_i = 10^{-7}cm^{-1}$, and an adult inhales 7300 m^3/yr:

$Q'3E-12$ μCi/yr

Table 14 presents the exposures resulting from fallout.

TABLE 14. FALLOUT DOSE ALGORITHMS

Radionuclide	Factors [illegible]	 [illegible]	Exposure Dose [illegible] at 1 m [illegible]	 [illegible]	 [illegible]	 [illegible]	Organ Dose [illegible] 1 cm [illegible]	 [illegible]	 50 cm [illegible]	Type [illegible]	 [illegible]
Tritium	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—	[illegible]	[illegible][a]	—
Carbon-14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—		[illegible]	—
Potassium-40	—	—	—	[illegible]	—	—	[illegible]	—		[illegible]	—
Iron-59	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—		[illegible]	—
Krypton-85	—	—	—	—	—	—	—	—		—	—
Rubidium-87	[illegible][b]	—	[illegible]	[illegible]	—	—	[illegible]	—		[illegible]	—
Strontium-89	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—		[illegible]	—
Strontium-90	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—		[illegible]	—
Ruthenium-103	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—		[illegible]	—
Ruthenium-106	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—		[illegible]	—
Iodine-129	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—		[illegible]	—
Iodine-131	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—		[illegible]	—
[illegible]	—	—	—	—	—	—	—	—		—	—
Cesium-134	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—		[illegible]	—
Cesium-137	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	—	[illegible]	—		[illegible]	—
[illegible]	[illegible][b]	—	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible][b]	—	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Radon-222	—	—	—	—	—	—	—	—		—	—
Radium-226	[illegible][b]	—	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Thorium-232	[illegible][b]	—	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Uranium-235	[illegible][b]	—	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Uranium-238	[illegible][b]	—	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Plutonium-238	[illegible]	—	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Plutonium-239	[illegible]	—	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Plutonium-240	[illegible]	—	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Plutonium-241	[illegible]	—	[illegible]	[illegible]	—	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
Polonium-210	[illegible][b]	—	[illegible]	[illegible]	—	—	[illegible]	—		[illegible]	—

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[a] Soluble (s); insoluble (i).

[b] Estimate

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IV ENERGY SYSTEMS

A. Coal for Direct Combustion

1. Coal Characteristics and Locations

The various types of coal are characterized by a number of parameters including heating value, ash content, moisture content, sulfur content, and the division of the organic portion of the coal into fixed carbon and volatile matter (volatile matter is that portion that can be driven off by heating the coal in a closed vessel; the fixed carbon is that portion which remains behind). The four main ranks of coal are anthracite, bituminous, subbituminous, and lignite.

Anthracite coals have heating values ranging from 13,000 to 15,000 Btu/lb[*] and are characterized by high fixed carbon (85% to 90%) and low moisture (2 to 5%) content [Ref. 19][†]. Over 96% of the nation's anthracite reserves are found in Pennsylvania.

The largest quantity of coal reserves is classified as bituminous. These coals have heating values from 12,000 to 15,000 Btu/lb, and fixed carbon content ranging from 45% to 78% [Ref. 19]. Moisture content ranges from 5% to 15%. The bulk of bituminous coal reserves lies in the eastern half of the United States.

Subbituminous coals occur mainly in the western half of the country. They have a low fixed-carbon content (37% to 45%) and heating values from 8000 to 11,000 Btu/lb. Moisture content can range from 18% to 35% [Ref. 19].

The youngest coals, geologically, are the lignites that are characterized by high moisture content (around 40%), low fixed-carbon content (25% to 30%), and low heating values (6000 to 7500 Btu/lb) [Ref. 19]. The major lignite deposits occur in eastern Montana, western North Dakota, and Texas.

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[*] The familiar English units are used in this coal section--one Btu/lb equals 2326 joules/kilogram.

[†] All heating values, fixed carbon contents and moisture contents reported here are on a mineral-matter-free basis. Mineral matter, or ash content varies widely from about 3% to over 30%, with typical values being about 5% to 10%.

The important parameters of coal composition for the purposes of this study are the uranium and thorium content. These parameters have not been measured to nearly the same extent as have the parameters previously discussed. Nevertheless, some measurements have been made, and these can serve as indicators of the levels of radioactive pollutants to be expected from coal processing and conversion activities.

In the 1950s, when extensive exploration for new uranium deposits was being carried out, it was discovered that some coal deposits in the western United States contained relatively high concentrations of uranium. The highest concentrations were found in lignite and the second highest in subbituminous coal. A small lignite deposit in South Dakota was found to contain up to 0.73% uranium [Ref. 20]. More typical figures for coal deposits containing higher than usual concentrations of uranium are 0.005% to 0.01% (50 to 100 ppm).

High concentrations of uranium in coal are the exception rather than the rule, however. In fact, the concentrations of radioactive elements in most coals are reported to be less than in common sedimentary rock. The uranium content of eastern bituminous and anthracite coals rarely exceeds 0.001% (10ppm).

The occurrence of higher concentrations of uranium in western coals is quite dependent on the geological history of the region. The most likely way in which uranium accumulates in coal is through ground water containing uranium dissolved from overlying volcanic rocks, or derived from hydrothermal sources, percolating through the coal beds, which capture it. Consequently, uranium-bearing coal typically occurs where the structure of adjacent rocks is permeable to water.

The U.S. Geological Survey Bulletin 1055 [Ref. 21] reported on some uranium-bearing coals in areas of the west that are considered likely candidates for future coal development. In southeastern North Dakota, some thin lignite seams (about 2 feet[a] thick) were found to contain an average of 0.013% uranium. The extent of the deposit sampled was about 27 million tons[a]. In eastern Montana (Carter County), a deposit of 16.5 million tons of lignite 1.5 to 8 feet thick was found to contain an average of 0.005% uranium. Neither of these deposits is considered economically minable at present.

In Sweetwater County, Wyoming, a much larger deposit of subbituminous coal was surveyed. A deposit lying within 75 feet of the surface, averaging about 2.5 feet thick and containing 700 million tons of coal, was sampled. The average uranium content was found to be 0.003%, with some localized concentrations ranging as high as 0.051%.

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[a] One foot equals 0.3048 m; one ton equals 907.2 kg.

The highest concentrations of uranium in coal reported in Bulletin 1055 were found in the LaVentana Mesa area, Sandoval County, New Mexico. Concentrations of up to 0.62% uranium were found, with the average concentration being 0.1%. This figure applies to a relatively small deposit of 132,000 tons.

As mentioned previously, these high concentrations of uranium are not typical and were discovered as part of a planned search for uranium-bearing minerals. If these values are not typical, then the question arises as to what typical values are. Most coal deposits in the United States have not been tested for their trace element content. However, over the past several years, concern over the environmental effects of trace element (including radionuclide) emissions from coal burning facilities has led to a number of trace element determinations. Coals from existing mines and from deposits expected to be mined in the future have been sampled and analyzed. Examples of determinations of uranium and thorium content for various coals, as reported in the literature, are shown in Table 15.

The figures in Table 15 represent average values; however, values for individual measurements within the same coal deposit can vary widely. For example, the values of uranium and thorium concentration for Powder River coals varied from 0.3 to 1 ppm and 1 to 3 ppm respectively (Ref. 22).

Because most coal deposits have not undergone testing for radioactive element concentration, it is impossible to determine how typical the values reported in Table 15 are. However, as these samples were taken from actively producing coal areas, or areas marked for future production, they

TABLE 15. URANIUM AND THORIUM CONTENT OF VARIOUS COALS
(ppm by Weight)

Location and Type of Coal	Uranium	Thorium	References
Appalachia (bituminous)	1.1	2.0	23
S. Illinois-West Kentucky (bituminous)	2.2	2.1	24
Power River Basin-Wyoming (subbituminous)	0.7	1.9	22
Navajo Reservation-New Mexico (subbituminous)	1.2	4.8	25
Kaiparowits Plateau-Utah (bituminous)	0.7	1.6	26

appear to be satisfactory for the purpose of calculating radionuclide emissions from coal conversion processes. In carrying out such calculations, it should be realized that wide excursions from the values reported in Table 15 are possible, and, in particular, much higher values can be encountered.

Another naturally occurring radioactive isotope of interest in coal conversion processes is potassium-40 (K-40). Potassium is a commonly occurring element in coal and potassium oxide (K_2O) is a minor constituent of coal ash. Concentrations of K_2O vary widely, as does the ash content itself. However, some average values can be determined and used for calculational purposes. Table 16 shows typical K_2O concentrations in the coals listed, along with the corresponding K-40 content. The K-40 content of the coal is based on the natural abundance of this isotope (0.0118%) in potassium.

As in the case of uranium and thorium content, the K-40 concentration can vary widely in coal samples taken from the same deposit. For example, the K-40 concentration of Powder River Basin coal samples can vary from 0.015 ppm to 0.052 ppm [Ref. 22].

TABLE 16. POTASSIUM-40 CONTENT OF VARIOUS COALS

Location and Type of Coal	Potassium Oxide (%)	Potassium-40 (ppm)	References
Appalachia (bituminous)	0.13	0.13	27
E. Illinois-W. Kentucky (bituminous)	0.19	0.18	24
Powder River Basin-Wyoming (subbituminous)	0.031	0.030	22
Navajo Reservation-New Mexico (subbituminous)	0.13	0.12	28
Kaiparowits Plateau-Utah (bituminous)	0.043	0.042	26

2. Mining Methods

The methods employed to extract coal from the many deposits located in the United States depend on the geological characteristics of the deposits, including coal depth, seam thickness, extent of the deposit, and so forth. Generally, coal mining is classified as either surface mining or underground mining, depending on whether the overburden is removed prior to recovery of the coal, or whether the overburden is left in place and the coal removed by underground operations.

a. Surface Mining

Surface mining can be carried out whenever the coal seam lies close enough to the surface to allow economical recovery of the coal. The economics of the operation is determined primarily by the thickness of the overburden in relation to the thickness of the coal seam. Overburden-to-seam thickness ratios of up to 30 can be economically surface-mined [Ref. 29].

In Appalachia, where coal seams tend to outcrop on hillsides, the most common surface-mining method is contour mining. With this method, a cut is made in the hillside above the coal seam, exposing the seam. The coal is removed by power shovels, which load it onto trucks. The cut is continued into the hillside until the overburden-to-seam thickness ratio becomes too high. The cut is continued along the hill in this manner and can extend for many miles.

The relatively flat terrain of the midwestern and northern Great Plains regions allows a type of surface mining called area mining to be carried out. With this method, a trench is excavated to expose the coal seam, with overburden removed by a large device called a walking drag line. The coal is removed by power shovels or front-end loaders and loaded onto trucks. As the coal is being removed, an adjacent, parallel cut is excavated. As this procedure is extended, the overburden is returned to mined out areas. Another version of area mining is open-pit mining in which a large pit is excavated and gradually widened to continually expose new coal. This method is especially appropriate to the very thick coal deposits found in the western United States.

Reclamation of surface mines can be carried out by grading over the back-filled areas, replacing the topsoil, which has been suitably stored, and either reestablishing a permanent vegetative cover or planting farm crops.

b. Underground Mining

Until recently, underground mining was the predominant method of coal mining in the United States. Now, however, the total tonnage of surface-mined coal surpasses that obtained by underground mining [Ref. 4].

Nearly all underground coal mining can be characterized as room and pillar mining. The name derives from the fact that a series of "rooms" are excavated in the coal seam, with "pillars" of coal left in place to support the roof of the mine. The rooms are formed typically by drilling, loading and blasting the seam and removing the coal by a loading machine. A relatively new innovation is a machine called a "continuous miner" that both scrapes the coal from the exposed face and loads it onto a conveyor belt, thus eliminating the need for blasting. After a room is formed, the roof is further strengthened by drilling holes in it and inserting bolts to generate compressive stresses.

The only other type of mining used to any extent in the United States is called long-wall mining. To carry out long-wall mining, two tunnels about 600 feet apart are excavated. Then a shearing machine works the coal face back and forth between the tunnels. Hydraulic jacks support the mine roof and are moved forward as mining progresses, allowing the roof to collapse. Long-wall mining allows a much higher recovery of the coal in place than does room and pillar mining. However, it accounts for only a small percentage of the underground coal production. The occurrence of surface subsidence tends to be much greater with long-wall than with room and pillar mining.

3. Coal Preparation

About 50% of the coal mined in the United States undergoes some sort of cleaning procedure before it is used. [Ref. 3] Nearly two-thirds of the coal burned in electric power plants is cleaned.

The first step in coal cleaning is breaking and sizing. In this operation, the coal is crushed to some preset upper limit of size. Coal is crushed in rotary mills and then screened to separate the coal that has been sufficiently crushed. Oversized coal is recycled to the crusher.

After crushing, the coal may be cleaned by a number of methods. The purpose of cleaning is to remove any foreign matter, such as dust, rock, shale, and so on, that is associated with the coal. The simplest method of coal cleaning is air washing, in which air is simply blown over the coal to remove dust and small particles.

There are several types of wet washing, all of which essentially make use of the difference in specific gravity between the coal and any foreign matter that might be present. Wet-washing methods include water/magnetite slurry flotation, gravity separation in a pulsating washbox, and froth flotation. On a nationwide basis, coal washing results in the removal of about 23%, by weight, of the run-of-mine coal [Ref. 29]. Most of the reject material is foreign matter, but about 5% of the feed coal is also removed [Ref. 29].

4. Coal Transportation

Once the coal has been mined, and possibly cleaned on-site, there are several modes of transportation that can be used to deliver it to the point of use. If the site of the power plant is near the mine, the coal is typically moved by conveyor belt or truck. For long distance transport, railroads are the most common method of shipment. About 70% of all coal shipped in the United States is carried by train [Ref. 29]. When the mine and the power plant are near navigable waterways, barges can be used. This method accounts for about 11% of the coal shipped [Ref. 29]. About 11% is shipped by truck [Ref. 29], and the remainder is accounted for by conveyors, tramways, or private railroads.

Another mode of coal shipment that has not yet come into widespread use is the coal-slurry pipeline. With this method, coal is first finely ground, then slurried with water so that it can be shipped through a pipeline much like crude oil. At the receiving end, the coal is dewatered with centrifuges, whereupon it is ready for burning. Only a single pipeline is in operation, shipping coal 270 miles from a mine at Black Mesa, Arizona, to a power plant in Nevada. Several longer pipelines have been proposed.

5. Electrical Power Generation

About 45% of the electrical power generated in the United States is produced in coal-fired power stations [Ref. 30]. As the demand for electricity grows and the nation attempts to reduce its reliance on petroleum and natural gas, the use of coal as a fuel in electricity generation will increase correspondingly.

The technology for producing electricity from the combustion of coal has been well established for many years. The basic steps involved are the combustion of the coal in a furnace, the capture of the combustion heat by a boiler that produces high-temperature steam under pressure, the expansion of the steam through a turbine that drives a generator, and the condensation of the steam exhausted by the turbine. The overall thermal efficiency of this process has increased in recent years to as high as 40% with modern boiler and heat-exchange technology.

In addition to the main components listed above, additional components required for electric power stations include heat-dissipation devices, such as evaporative cooling towers and cooling ponds; stack gas cleanup equipment, such as electrostatic precipitators and scrubbers; and coal preparation equipment. These additional units are also consumers of power, and their use may reduce the coal-to-electricity conversion efficiency by up to 10% [Ref. 29].

Typical sizes of new power-generating stations are on the order of 1000 MWe, although facilities of up to 3000 MWe have been proposed. These large stations are designed to be base-load facilities, supplying power almost continuously; peak load requirements are met by older, smaller plants and gas turbines.

New source performance standards for coal-fired boilers, promulgated by the EPA, limit the quantities of pollutants emitted by these facilities. For particulates, sulfur dioxide, and nitrogen oxides, EPA new source performance standards are 1.2, 0.1, and 0.7 lb, respectively, per 10^6 Btu of coal burned. Because different coals have varying ash and sulfur content and heating value, the level of control required is dependent on the type of coal used. It also depends on the type of coal-firing employed. For example, cyclone furnaces release only about 50% of the ash in the coal as fly ash, whereas conventional tangentially fired furances release 80% to 90%.

The radiological impact of coal combustion depends to a large extent on the environmental controls required to limit the emissions of other pollutants, because it is the release of radionuclides with the stack gases that will have the greatest potential effect.

The siting of large coal-fired power plants is a complex matter involving the availability of water for cooling, the location of the coal deposits, the location of demand centers, the potential for violating air quality standards, and so forth. In the eastern states, plants have tended to be sited near demand centers since coal transportation distances are not large, and stringent air pollution controls have been only recently required. In the west, the recent trend has been to site coal-fired plants near the resource and transmit the electricity to load centers via high voltage power lines. Due to existing air quality problems in may urban areas, the siting of new coal-fired power stations in or near urban areas is virtually impossible.

Advanced technologies for converting coal to electricity promise increased efficiency and greater environmental acceptibility. Among these are the low-Btu gasification of coal followed by combustion in a gas turbine-steam turbine combined cycle, and fluidized-bed combustion of coal. These and other technologies are under development by ERDA and private companies, with the expectation that they will be introduced commercially by the mid to late 1980s.

6. People

Both the number of people employed in the various facilities and the population density in the surrounding areas are important for assessing the occupational and general population health effects of radiological emissions from fossil-fuel technologies.

Employment levels for coal mining vary widely due to the variations in depth and thickness of the seam, type of mining method employed, and so forth. The population density adjacent to mining areas varies even more widely from relatively high densities for eastern mines to relatively low densities for western mines.

Employment levels required for the operation of coal-fired power plants and the population densities adjacent to these plants also vary widely. Many plants are located within or adjacent to large urban complexes and others are located in sparsely populated regions.

7. Radiological Aspects

The emission of radionuclides from the combustion of coal and the associated coal fuel cycle is strongly dependent on the type of coal used and its content of uranium and thorium, their daughter products, and potassium. As shown in the Tables 15 and 16, these properties vary from one coal region to the next, so that each region should be considered separately.

In the calculation of radionuclide emissions, it will be assumed that all uranium and thorium daughter products are in secular equilibrium. This is generally a good assumption due to the very old geological age of most coal deposits. In some cases, there has been evidence of selective leaching of some daughter products with repect to the parent uranium or thorium. However, in the absence of any particular evidence for the coals under consideration, secular equilibrium will be assumed.

The examination of radiological effects will proceed in a step-by-step method beginning with coal mining and ending with coal combustion.

a. Mining

The predominant radionuclide emission from coal mining is radon, which is released during the exposure of coal seams and the breakup of coal being mined. Any operation that increases the surface area of the coal exposed to the atmosphere will result in the additional diffusion of radon into the air. Coal mining can produce individual coal pieces ranging in size from fine powder to several feet in length. The amount of radon released will vary inversely with the size of the mined coal pieces.

The amount of radon initially present in the coal is a function of the uranium and thorium content, because the isotopes radon-222 and radon-220 are members of the uranium-238 and thorium-232 decay series, respectively.[a] Assuming secular equilibrium, the radon isotopes should have the same activities as the parent uranium and thorium isotopes. The concentrations of radon-222 and radon-220 in the coals for which uranium and thorium determinations have been made are shown in Table 17.

TABLE 17. RADON-222 AND RADON-220 CONCENTRATIONS IN VARIOUS COALS

Location and Type of Coal	Concentration		Activity (pCi/g coal)	
	Rn-222	Rn-220	Rn-222	Rn-220
Appalachia (bituminous)	2.4×10^{-18}	2.4×10^{-22}	0.37	0.22
N. Illinois-W. Kentucky (bituminous)	4.8×10^{-18}	2.5×10^{-22}	0.73	0.23
Powder River Basin-Wyoming (subbituminous)	1.5×10^{-18}	2.3×10^{-22}	0.23	0.21
Navajo Reservation-New Mexico (subbituminous)	2.6×10^{-18}	5.7×10^{-22}	0.40	0.52
Kaiparowits Plateau-Utah (bituminous)	1.5×10^{-18}	1.9×10^{-22}	0.23	0.17

It is extremely difficult to calculate the exact amount of radon that is released when coal is mined. However, some rough assumptions can be made that will give an order-of-magnitude estimate as to how much is released. First of all, the concentration of radon in coal is extremely low, as can be observed from Table 17. These concentrations amount to approximately 1 atom of radon per gram of coal, or 1400 atoms per 1000 cubic centimeters. At these low concentrations, the rate of diffusion is likely to be very small, because the driving force behind diffusion is a concentration gradient. If we assume, as an upper limit, that all the radon within 1 cm of the surface of a coal chunk is released during mining, and that the average coal chunk is about a foot (30 cm) across, then approximately 20% of the radon would be released during mining.

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[a] In subsequent discussion, only the uranium-238 and thorium-232 decay series will be included, because the low natural abundance of uranium-235 (0.715%) results in an activity for this isotope and its daughters of only 4.5% of uranium-238 and its daughters.

In the calculation of the amount of radon released during the mining of the coal necessary to support a 1000 MWe power plant, certain values are assumed for the heating values of different coals. A typical heating value for Powder River coal is 8200 Btu/lb; for Navajo coal, 8500 Btu/lb; for Utah coal, 10,800 Btu/lb; for Illinois coal, 11,000 Btu/lb; and for Appalachian coal 12,500 Btu/lb. On the basis of these heating values and an assumed thermal efficiency of 35%, the amounts of coal that have to be mined to support the operation of a 1000-MWe power plant are: Powder River coal, 14,300 tons per day; Navajo coal, 13,800 tons per day; Utah coal, 10,800 tons per day; Illinois coal, 10,600 tons per day; and Appalachian coal, 9400 tons per day.

Table 18 shows the activity of the radon-222 and radon-220 released per day when the above levels of mining occur, for 1%, 5%, and 20% release of the radon trapped in the coal. For comparison, it should be noted that the average natural release rate of radon-222 above soil is 150 μCi per acre[6] per day.

TABLE 18. RATE OF RELEASE OF RADON FROM COAL MINING
IN SUPPORT OF A 1000-MWe POWER PLANT

	Release Rate of 1%, 5%, and 20% of Radon Trapped in Coal (μCi/day)					
	1%		5%		20%	
Location and Type of Coal	Rn-222	Rn-220	Rn-222	Rn-220	Rn-222	Rn-220
Appalachia (bituminous)	32	19	160	94	630	380
N. Illinois-W. Kentucky (bituminous)	70	22	350	110	1400	440
Powder River Basin-Wyoming (subbituminous)	30	27	150	140	600	550
Navajo Reservation-New Mexico (subbituminous)	50	65	250	330	1000	1300
Kaiparowits Plateau-Utah (bituminous)	23	17	110	83	450	330

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[6] One acre equals 4047 m^2.

Radon-222 has a half-life of 3.82 days, so that when it is emitted it will be swept downwind from the mine where it will ultimately decay through the series polonium-218→lead-214→bismuth-214→polonium-214→lead-210, the latter product having a half-life of 22 years. Radon-220 has a half-life of only 56 seconds, however, so that most of it will decay while still in the mine environment. The solid (particulate) daughter products polonium-216→lead-212→bismuth-212→polonium-212→thallium-208 will adhere to the dust particles generated by mining activities, most of which will settle out near the mine.

In underground mining operations, the presence of radon-222, radon-220 and their daughters in the mine atmosphere may pose an occupational health hazard. The concentration of these species in the mine atmosphere depends not only on the uranium and thorium content of the coal, but also on the ventilation rate of the mine.

In 1975, a survey was made of the presence of radon-222 and radon-220 daughters in 223 operating underground mines in 15 coal-producing states [Ref. 31]. According to this survey, there appears to be no significant health hazard from inhalation of radon-222 and radon-220 daughters in underground mines.

One final possible route of exposure for radionuclides in uranium-bearing coal is mine acid drainage. This is a phenomenon by which groundwater drainage through exposed coal seams converts pyrite materials in the coal to sulfuric acid. In the Appalachian coal region, the sulfuric acid content of mine drainage is as high as 1700 ppm. Because uranium is capable of forming soluble sulfate complexes in the presence of sulfuric acid, the leaching of uranium from coal is a potential problem. Alpha activity in excess of 10 pCi/l, originating from dissolved uranium, has been reported in the drainage from some eastern Pennsylvania coal fields where the uranium concentration ranged from 10 to 140 ppm [Ref. 32]. To meet EPA-mandated standards, mine-drainage water is usually treated with lime to neutralize the acidity. With this treatment, many of the metals in solution are precipitated out if the pH is allowed to rise above 7. The formation of a low solubility uranium oxide hydrate in basic solution could help to reduce the alpha activity of the mine drainage.

b. Coal Preparation

The main effluents from coal preparation are the solid wastes consisting of rejected noncoal material, and the aqueous effluent termed "blackwater." Up to 2 tons of blackwater containing 4% to 5% suspended coal fines can be generated per ton of coal washed [Ref. 29].

The solid waste, averaging 23% by weight of the mined coal, is typically stored on the surface in large piles. Although runoff from these piles can pose a serious general water pollution problem (if proper impoundment techniques are not employed), unless the content of radioactive species in these materials is significantly different from that of the soils in the area, radioactive contamination of surface waters should not be a problem.

The blackwater from coal washing can be sent to a tailings pond where the solids are allowed to settle out, and the clarified water can be recycled to the coal preparation plant. It is possible that leakage from such tailings ponds could contaminate local groundwater. If the tailings pond water were acidic due to a high content of pyritic material in the coal, then significant quantities of those elements, including uranium, could be dissolved in it. The extent of possible contamination of ground water is almost impossible to quantify.

The thermal drying of coal to reduce its moisture content is a source of emissions to the air. However, the numerical details are left to those sections in this report in which coal drying is included as an integral requirement of the coal conversion operation.

c. Coal Combustion

The dominant source of radioactive emissions in the coal-to-electricity fuel cycle will be the electrical power generating stations. All the radioactive elements in the coal entering these generating stations will ultimately exit in the form of waste materials discharged to the environment--either as emissions to the atmosphere or as solid waste.

With the exception of radon, all the emissions of radionuclides to the atmosphere will be associated with the discharge of fly ash resulting from coal combustion. To meet the EPA new source performance standards of 0.1 lb particulates per million Btu fired, the fly ash discharge must be reduced by at least 98%. This requirement effectively limits the release of radionuclides as well. The use of electrostatic precipitators or venturi scrubbers to remove fly ash from stack gases can result in removal efficiencies of 99.5% or greater. In fact, several proposed new coal-fired power plants have been designed to use equipment of this efficiency even though the equipment exceeds EPA requirements. This situation primarily results from stricter state emission standards, or standards for plume opacity.

Table 19 shows the quantities of particulate matter (fly ash) emitted in the operation of a 1000-MWe power plant for each type of coal considered in this chapter. Typical ash contents of the coals are shown along with the particulate emissions associated with both the EPA standard and a 99.5% removal efficiency. The calculations of the emissions were made under the assumption of a 35% net power plant thermal efficiency, full capacity operation, and an 85% conversion of coal ash to fly ash. It is clear from the table that 99.5% control is sufficient to meet the EPA standard by a large margin for all coals except Navajo coal from New Mexico. Due to its high ash content, this coal would require a removal efficiency of about 99.6% to meet the standard.

We will first consider the release of radon-222 and radon-220, which are the only radionuclides released as gases. In the preparation of the coal for firing, it is first pulverized, then blown into the boiler with a stream of air. It is probable that during pulverization most of the trapped radon is released, and that any remaining would be released during combustion.

TABLE 19. PARTICULATE EMISSIONS FROM A 1000-MWe COAL-FIRED POWER PLANT

Coal	Btu/lb	% Ash	Tons of Particulates/Day	
			$0.1 \text{ lb}/10^6$ Btu	99.5% Control
Appalachia	12,500	9	12	3.7
Illinois-W. Kentucky	11,000	11	12	5.0
Powder River	8,200	6	12	3.6
Navajo	8,500	25	12	13
Utah	10,800	7	12	3.2

TABLE 20. RELEASE OF RADON ISOTOPES FROM A 1000-MWe POWER PLANT

Coal	Radon Release (µCi/day)	
	Rn-222	Rn-220
Appalachia	3140	1870
Illinois-W. Kentucky	7050	2220
Powder River	2980	2720
Navajo	5000	6500
Utah	2260	1670

Because these operations take place in a totally enclosed system, most of the released radon will be swept into the boiler and exit the facility along with the stack gases. Table 20 shows the quantities of radon isotopes released for a 1000-MWe power plant, if total release of all radon present in the coal is assumed. These values should be considered as upper limits, due to the potential for radon losses prior to combustion. Also, in the case of radon-220, due to its short half-life, some decay to daughter products will occur during and after combustion, and these will adhere to ash particles most of which will be captured by the fly ash control equipment.

The emission of other radionuclides in the uranium-238 and the thorium-232 decay series, as well as of potassium-40, can be calculated in a straightforward way by assuming that all these elements adhere to the ash when the coal is combusted, and subsequently follow the same pathways as the ash itself--10% to 20% going to bottom ash with the remainder emitted as fly ash, most of which is captured. Based on these assumptions, the total quantities of radionuclides emitted from a 1000-MWe power plant are shown in Table 21. A particulate removal efficiency of 99.5% has been assumed, except in the case of Navajo coal where a slightly higher efficiency has been assumed so that the EPA standard of 0.1 pound of particulates per million Btu is met. The emission levels of uranium and thorium daughters in Table 21 assume, of course, that secular equilibrium is maintained throughout the combustion and emission processes.

In practice, a number of phenomena will cause the actual emission levels of some radionuclides to differ from those shown in Table 21. The most obvious of these phenomena is the disturbance of secular equilibrium. In the case of radon-222 and its daughters, this disturbance will probably be small because of the length of the half-lives of radon-222 (3.82 d) and its immediate daughters polonium-218 (3.05 min), lead-214 (26.8 min), and bismuth-214 (19.7 min), compared to the brief time scale of coal combustion and exit via tall stacks--on the order of a few tens of seconds. Radon-220 (56 s), however, and its daughter polonium-216 (0.14 s) have relatively short half-lives compared to this time scale. The observed effect would be values of polonium-216 and lead-212 enhanced above secular equilibrium, and a reduced value of radon-220 compared to that shown in Table 20. The species below lead-212 in the decay series will not be appreciably affected because of the relatively longer half-life of lead-212 (10.6 h).

The other phenomenon that can significantly alter the values shown in Table 21 is the observed tendency for some elements to become concentrated in the fly ash relative to the bottom ash, and to be further concentrated in the particulate matter exiting the fly ash removal equipment relative to that entering. Several recent studies have indicated that uranium, lead, and polonium isotopes tend to be concentrated in fly ash in this fashion [Ref. 28, 33, 34]. Thorium, radium, and potassium do not appear to be concentrated to any appreciable degree. The degree of concentration of any element is dependent on the type of boiler employed (cyclone or tangential) as well as on the devices used to remove fly ash from the stack gases (electrostatic precipitator, venturi scrubber, or cyclone).

The tendency of the elements uranium, lead, and polonium to concentrate in fly ash could significantly increase the radioactivity of emitted particulates because 7 out of 14 members of the uranium-238 decay series are isotopes of these elements, as are 3 out of 11 of the thorium-232 series. Isotopes of other elements in these series have not been tested. The increase in emitted radioactivity resulting from this concentration can be calculated using some average concentration factors. As a rule of thumb, a factor of 5 can be used to express the concentration of uranium, lead, and polonium in emitted fly ash relative to the factor of 1 obtained by assuming that these elements are evenly distributed in all the ash. This rough number averages over several types of boiler and fly ash collection configurations, and in some configura-

TABLE 21. EMISSION OF RADIONUCLIDES IN PARTICULATE MATTER FROM A 1000-MWe POWER PLANT: NO ELEMENTAL CONCENTRATION IN FLY ASH ASSUMED (μCi/day)

	Coal Type				
Radionuclide	Appalachia	Illinois-W. Kentucky	Powder River	Navajo	Utah
Uranium-238	13.3	30.0	12.7	17.5	9.6
Thorium-234	13.3	30.0	12.7	17.5	9.6
Protactinium-234	13.3	30.0	12.7	17.5	9.6
Uranium-234	13.3	30.0	12.7	17.5	9.6
Thorium-230	13.3	30.0	12.7	17.5	9.6
Radium-226	13.3	30.0	12.7	17.5	9.6
Radon-222	a	a	a	a	a
Polonium-218	13.3	30.0	12.7	17.5	9.6
Lead-214	13.3	30.0	12.7	17.5	9.6
Bismuth-214	13.3	30.0	12.7	17.5	9.6
Polonium-214	13.3	30.0	12.7	17.5	9.
Lead-210	13.3	30.0	12.7	17.5	9.6
Bismuth-210	13.3	30.0	12.7	17.5	9.6
Polonium-210	13.3	30.0	12.7	17.5	9.6
Thorium-232	7.9	9.4	11.6	27.6	7.1
Radium-228	7.9	9.4	11.6	27.6	7.1
Actinium-228	7.9	9.4	11.6	27.6	7.1
Thorium-228	7.9	9.4	11.6	27.6	7.1
Radium-224	7.9	9.4	11.6	27.6	7.1
Radon-220	a	a	a	a	a
Polonium-216	7.9	9.4	11.6	27.6	7.1
Lead-212	7.9	9.4	11.6	27.6	7.1
Bismuth-212	7.9	9.4	11.6	27.6	7.1
Polonium-212	5.1	6.0	7.4	17.7	4.5
Thallium-208	2.8	3.4	4.2	9.9	2.6
Potassium-40	30.0	47.2	10.5	33.4	11.2
Total	290	521	280	509	200

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[a] See Table 20.

times uranium would be less concentrated than lead, for example, and in others the opposite would be true. However, this number will serve to illustrate the effect.

In calculating increases in emitted radionuclides, it is important to note that only concentrations of relatively long-lived isotopes will be affected; concentrations of short-lived isotopes would result only in rapid decay back to equilibrium values. Thus, concentrations of polonium-214 (164 μs), polonium-216 (0.15 s), and polonium-212 (0.3 μs) would not increase emitted radioactivity.

Using the factor of 5 discussed above, along with the preceding qualifications, the calculated emission of radionuclides from a 1000-MWe power plant are shown in Table 22. Elements other than uranium, lead, and polonium are assumed to exhibit no concentration in emitted fly ash.

As can be seen from Table 22, the assumptions made about the concentration of uranium, lead, and polonium in emitted fly ash result in an increase in emitted particulate matter by a factor of more than two, for all the coals considered. An important point to be noted in relation to the elemental concentration effect is that the particulate matter emitted by collection devices of various kinds tends to be very fine--about one micron or less in diameter. It is precisely these particles that are not filtered out during respiration and that tend to become lodged in the lungs and bronchial passages. Thus, those particulates on which certain radioactive elements tend to concentrate are precisely those most capable of delivering radionuclides to susceptible organs.

The ultimate disposition of the remaining radioactive elements not emitted from the stacks will be the ash disposal pond, which will receive the 99+% of the original ash in the coal recovered as bottom ash and removed from the stack gases. In the case of power plants located near western surface mines, the ash can be returned to the mine and buried.

Because the ash will be more or less permanently contained in the disposal ponds, there is little chance of further airborne release of radionuclides, with the exception of radon. The ash disposal piles will contain in secular equilibrium all the elements in the uranium-238 and thorium-232 decay series, including radium-226 and radium-224 which decay to radon-222 and radon 220, respectively. Because it is possible for radon to diffuse out of the ash piles once it is formed, radon emission could be a problem. This applies particularly to radon-222, because radon-220 probably decays before a significant diffusion can take place.

To calculate the maximum impact of radon emissions from ash storage areas, we assumed that ash was collected and stored over the 30-year lifetime of a 1000-MWe power plant at a depth of 30 feet with a density of 60 lb per cubic foot [Ref. 26]. Table 23 shows the resulting amount of radium-226 present in the ash, assuming secular equilibrium with the parent uranium-238; the area of the pile; and the rate of radon-222 release if all radon-222 formed from the decay of radium-226 is released. It was also assumed that the power plant was operated at an average capacity factor of 75%.

TABLE 22. EMISSION OF RADIONUCLIDES IN PARTICULATE MATTER FROM A 1000-MWe POWER PLANT: CONCENTRATION OF URANIUM, LEAD, AND POLONIUM IN FLY ASH ASSUMED (µCi/day)

	Coal Type				
Radionuclide	Appalachia	Illinois-W. Kentucky	Powder River	Navajo	Utah
Uranium-238	66.5	150.0	63.5	87.5	48.0
Thorium-234	13.3	30.0	12.7	17.5	9.6
Protactinium-234	13.3	30.0	12.7	17.5	9.6
Uranium-234	66.5	150.0	63.5	87.5	48.0
Thorium-230	13.3	30.0	12.7	17.5	9.6
Radium-226	13.3	30.0	12.7	17.5	9.6
Radon-222	a	a	a	a	a
Polonium-218	66.5	150.0	63.5	87.5	48.0
Lead-214	66.5	150.0	63.5	87.5	48.0
Bismuth-214	13.3	30.0	12.7	17.5	9.6
Polonium-214	13.3	30.0	12.7	17.5	9.6
Lead-210	66.5	150.0	63.5	87.5	48.0
Bismuth-210	13.3	30.0	12.7	17.5	9.6
Polonium-210	66.5	150.0	63.5	87.5	48.0
Thorium-232	7.9	9.4	11.6	27.6	7.1
Radium-228	7.9	9.4	11.6	27.6	7.1
Actinium-228	7.9	9.4	11.6	27.6	7.1
Thorium-228	7.9	9.4	11.6	27.6	7.1
Radium-224	7.9	9.4	11.6	27.6	7.1
Radon-220	a	a	a	a	a
Polonium-216	7.9	9.4	11.6	27.6	7.1
Lead-212	39.5	47.0	58.0	138.0	35.5
Bismuth-212	7.9	9.4	11.6	27.6	7.1
Polonium-212	5.1	6.0	7.4	17.7	4.5
Thallium-208	2.8	3.4	4.2	9.9	2.6
Potassium-40	30.0	47.2	10.5	33.6	11.2
Total	[illegible]25	1280	631	1110	659

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[a] See Table 20.

The maximum emanation rate of radon-222 as shown in Table 23 is 10.5 Ci/day over 245 acres, or 42,900 μCi per acre per day. The average natural background emanation from soil is 150 μCi per acre per day [Ref. 35]. Therefore, it appears that radon emission from ash piles is a rather significant effect.

TABLE 23. MAXIMUM RADON-222 RELEASE FROM 30-YEAR
ASH STORAGE PILE FROM 1000-MWe POWER PLANT

Coal Type	Area of Pile (acres)	Ra-226 Content (grams)	Rn-222 Release (Ci/day)
Appalachia	176	26.2	4.6
Illinois-W. Kentucky	245	59.5	10.5
Powder River	179	25.6	4.5
Navajo	721	42.0	7.4
Utah	159	19.3	3.4

Even though it is not probable that all the radon formed within the ash pile is released to the air, the effect could still be significant. Assuming that the radon release percentage from coal ash piles is similar to that from uranium mill tailings piles, i.e., about 5% [Ref. 8, 12], the release rate is still 14 times the natural background rate for the maximum case (Illinois-W. Kentucky coal) and 3.4 times natural background for the minimum case (Navajo coal).

Another potential long-term problem resulting from ash disposal is the contamination of groundwater through leaching of the ash piles. Radioactive elements can be leached along with other constituents of coal ash, resulting in radioactive contamination of groundwater. Although it is nearly impossible to quantify the extent of such contamination, the problem should be pointed out so that appropriate monitoring can take place. Steps taken to control ash pile leaching, such as the lining of disposal ponds with impermeable material, will effectively control radioactive contamination as well.

B. Coal Gasification and Liquefaction

The use of the nation's vast reserves of coal to produce clean liquid and gaseous fuels is viewed by many as a potential long-term solution to dwindling supplies of petroleum and natural gas. Neither coal gasification nor liquefaction are in commercial operation today. However, first generation coal gasification technology is available, and two substitute natural gas (SNG) plants based on Lurgi gasification technology are being planned for the Four Corners area of New Mexico. Coal liquefaction technology is still in the R&D stages, and commercial operations are not expected until the mid-1980s, at the earliest.

1. Coal Gasification Technologies

The synthesis of high-Btu gas or SNG (primarily methane) from coal involves two basic steps: first, the gasification of coal by reaction with steam and oxygen to form a medium-Btu synthesis gas; and second, the catalytic reaction of the hydrogen and carbon monoxide in the synthesis gas (after suitable adjustment of the H_2/CO ratio) to form methane. Fifteen separate processes have been proposed, tested, or are in commercial operation to accomplish the first step of coal gasification. These processes differ in the temperature and pressure at which gasification takes place, the nature of the medium in which gasification reactions occur, the method of feeding the coal, steam, and oxygen into the reactor, and so forth.

Beyond the gasification step, the conversion of synthesis gas to methane follows basically the same steps for each process. These steps generally include: (1) quenching or scrubbing of the raw synthesis gas to remove tars and oil and/or particulate matter formed in the reactor, (2) CO shift, in which the H_2 to CO ratio is adjusted to 3:1 by reacting excess CO with steam to form H_2 and CO_2, (3) purification of the synthesis gas, involving primarily removal of the acid gases CO_2 and H_2S, (4) catalytic methanation to form the 900 to 1000 Btu-per-SCF (standard cubic foot) product gas, and (5) removal of water vapor from the product gas and compression of the gas to pipeline pressure.

Numerous plans for using coal to produce SNG have been announced by a number of pipeline companies. The plants closest to the construction stage are those planned by El Paso Natural Gas and WESCO (Western Gasification Company) for the Four Corners area of New Mexico. These plants are based on the Lurgi gasification process and will produce approximately 288 million and 275 million SCF per day, respectively, of pipeline quality gas.

In the Lurgi process, crushed coal is fed in batches into the top of the reactor, and steam and oxygen are injected at the bottom. Gasification takes place at high temperature and pressure (1400°F and 400 psi). Ash is removed through a grate at the bottom of the reactor. The Lurgi gasifier is termed a "fixed bed" reactor because the coal remains fixed in place as gasification is carried out.

First generation plants plan to use the Lurgi process because it is commercially available and its use has been reliably demonstrated over a period of many years. Because of certain drawbacks in the operation of Lurgi gasifiers, second or third generation gasification plants will undoubtedly use more advanced processes such as the ERDA-sponsored Synthane process, or the Institute of Gas Technology (IGT) Hygas process, as these technologies become available for commercial application.

2. Coal-Liquefaction Technologies

To date, no commercial coal-liquefaction plants have been planned because the technology is not at a sufficient level of development to bring a commercial plant on stream with any reasonable guarantee of success. However, a number of pilot plants are being operated under sponsorship of ERDA or private industries, and several demonstration plants are in the planning stages. It is generally believed in the industry that no full-sized commercial plants (30,000 bbl/day or larger) will be on-line before 1985.

The processes for converting coal to liquid fuels fall into three main categories. These are: gasification/Fischer-Tropsch synthesis, pyrolysis, and coal dissolution. Gasification of coal followed by Fischer-Tropsch synthesis to yield gasoline and other hydrocarbon byproducts is the only one of the three processes that is currently in commercial operation--a 6600 ton/day plant is being operated by the South African Gas and Oil Company (SASOL). Due to the high costs and low efficiency of this technique, it is unlikely that it will be used to any significant degree in the United States.

Coal pyrolysis is a technique for extracting oil, gas, and char (a solid product consisting mainly of carbon and ash) from coal by heating it to high temperatures in the absence of air. The COED (Char-Oil-Energy-Development) process developed by the FMC Corporation has been tested in a 36 ton/day pilot plant near Princeton, New Jersey. Other coal pyrolysis methods have been tested at the pilot plant stage by Garrett Research and Development and The Oil Shale Corporation. In all pyrolysis methods, the yield of oil is low compared with the other methods for making liquid fuels from coal.

The process of coal dissolution (also known as solvent refining or solvent extraction) has the greatest potential for efficiently producing liquid hydrocarbon fuels from coal. The two basic steps in this process are the dissolution of the organic matter in the coal in a process-derived solvent, and hydrogenation of the resulting product to yield a liquid hydrocarbon fuel. Several variants of the coal dissolution process that have been tested at the pilot plant level are the Solvent Refined Coal (SRC) process of Pittsburgh and Midway Coal Company, the Consol Synthetic Fuel (CSF) process of Consolidation Coal Company, the H-Coal process of Hydrocarbon Research, Incorporated, the Gulf catalytic coal liquids process, the Exxon donor solvent process, and the ERDA Synthoil process. The H-Coal process appears to be one of the most promising for further development, and considerable analysis has been done on it using information that has been made public.

In the conversion of coal to liquid fuels via the H-Coal process, dissolution and hydrogenation are carried out in the same step in the presence of a catalyst. The slurried coal is reacted with hydrogen in an ebullating bed reactor at 850°F and 2700 psi. A cobalt-molybdenum catalyst is continuously added to the reactor as spent catalyst is removed. After gases and unreacted solids are separated from the mixture, synthetic crude oil is recovered from fractionation of the resulting liquid.

Initial testing of the H-Coal process has been carried out in a 3-ton/day pilot plant at the Hydrocarbon Research, Inc. (HRI) facilities at Trenton, New Jersey, under the sponsorship of Ashland, ARCO, Standard of Indiana, and Exxon. In addition, ERDA and HRI are planning a 600-ton/day pilot plant at Catlettsburg, Kentucky, to test the commercial feasibility of the H-Coal process. Industrial sponsors include those mentioned above (except Exxon), the Electric Power Research Institute, and Sun Oil.

In all of the coal dissolution processes discussed above, large amounts of hydrogen (15,000 to 20,000 SCF per ton of coal) are consumed. In general, the hydrogen can be supplied by gasifying unreacted coal solids (char) or by steam reforming byproduct hydrocarbon gases. If necessary, additional hydrogen can be provided by gasifying some of the feed coal.

3. People

Although coal gasification and liquefaction are not particularly labor-intensive processes, the large sizes of the facilities envisioned will require substantial numbers of employees at any particular site.

El Paso Natural Gas Company estimates that about 880 employees will be required to operate its proposed 288 million SCF/day SNG plant in New Mexico [Ref. 36]. Western Gasification Company estimates a somewhat lower figure, 610, for its proposed 275 million SCF/day plant [Ref. 25].

For coal liquefaction, the plant size characteristic of a mature industry would be on the order of 100,000 barrels of liquid products per day. This size facility would employ about 1400 people [Ref. 37].

4. Radiological Aspects

a. Coal Gasification

There are two potential radiological problems in coal gasification. One is the emission of radionuclides at the plant site, and the other is possible contamination of the product SNG which will later be used in homes and industries. We will deal with the latter question first, because it can be handled with a simple calculation. All the analysis in this section will be based on the Bureau of Reclamation's Environmental Impact Statement (EIS) for Western Gasification Company's (WESCO) proposed 275-million-SCF/day plant in New Mexico [Ref. 36]. Although a similar EIS has been carried out for El Paso's proposed plant [Ref. 25], the WESCO EIS is somewhat more detailed and more suitable for the purposes of this section. The coal to be used in the plant is the Navajo Reservation subbituminous coal whose properties were listed in Section IV-A. At this time, no other detailed analyses of coal gasification based on other coal types have been published.

The problem of radioactive contamination of the product SNG is essentially a problem of radon contamination, because virtually all particulate matter is removed from the gas during processing. Gasification of the coal is carried out in an enclosed, pressurized vessel, and probably all the radon in the coal is released during gasification and enters the synthesis gas. The various physical and chemical processes that are subsequently employed to clean the gas and convert it to methane will have little effect on the radon, since radon is an inert gas. It will be carried through the gasification and synthesis steps, as are the small amounts of nitrogen and argon present in the oxygen used for gasification.

To calculate the maximum amount of radon present in the product SNG, we assume that all the radon initially present in the coal fed to the gasifiers emerges in the product. In the WESCO plant design, 24,820 tons of coal would be converted to 275 million SCF per day. With a radon-222 activity of 0.40 pCi/g for Navajo coal (see Section IV-A), 9.0 μCi will enter the gasifiers each day. (Radon-220 is not considered due to its short half-life.) The resulting maximum concentration in the product SNG will thus be 33 pCi/SCF or 1.2 pCi/l.

The significance of this concentration can be assessed in terms of the amount of radon-222 present in natural gas reservoirs. Various surveys of natural gas wells have indicated radon-222 concentrations of 0.2 to 1450 pCi/l, with an average concentration of 37 pCi/l [Ref. 38]. Because these levels of radon contamination have been shown to have insignificant health effects on natural gas users [Ref. 38], we may conclude that the potential health impact of 1.2 pCi/l of radon-222 in SNG is negligible.

The emission of radionuclides at the plant site is calculated in a fashion similar to that for electric power plants, that is by examining the disposition of the mineral matter (ash) component of the coal, realizing that most of the uranium-238, thorium-232, their daughters, and potassium-40 will be incorporated in it. The bulk of the emissions of radionuclides to the air will occur from the coal-fired steam boilers that provide steam to the gasifiers. These boilers consume 3870 tons/day of washed coal and discharge 0.82 tons/day of particulate matter to the air, after stack gas clean-up operations. A minor secondary source of emissions is a steam superheater which burns tar oil--a byproduct of gasification--and emits 0.019 tons/day of particulate matter. A small amount of coal dust (0.016 tons/day) is emitted from coal-handling equipment controlled by fabric filters or cyclones.

The rest of the ash that enters the plant is recovered as bottom ash from the gasifier (6530 tons/day), or bottom ash plus collected fly ash from the steam boiler (610 tons/day), and is returned to the mine for burial. Approximately 560 tons of ash that is present in the coal rejected from the boiler coal-washing facility is removed to a disposal pond rather than buried with the ash.

Small amounts of ash and coal dust that exit the gasifier along with the synthesis gas are removed by a scrubber. The scrubber effluent is treated for removal of phenols, ammonia, and hydrogen sulfide, then sent to a biological treatment/settling pond where impurities are removed so that the waste water can be recycled. The ash and coal fines that settle out in this pond become part of the sludge that is eventually removed to the mine and buried. It is possible that the scrubber effluent might be slightly enriched with lead and polonium isotopes, since these volatile elements tend to vaporize to some extent in the gasifier, and are condensed in the scrubber. The 3.5 million gallons of treated waste water would contain about 5 ppm of suspended solids [Ref. 39]. If this water is discharged rather than recycled to the evaporative cooling towers, its radioactivity level would be 0.2 pCi/l, assuming all solids are coal ash.

To calculate radon emissions, we can assume that all the radon in the boiler feed coal is released, part during crushing, and the remainder during combustion. For the gasifier feed coal, the only source of radon emission will be crushing, since radon released during gasification will be retained in the product SNG. Because the gasifier feed coal is crushed (to less than 1-1/2 in) rather than pulverized, we may assume, as an upper limit, that 50% of the radon in this coal is released.

The emissions of radionuclides resulting from the sources discussed above are shown in Table 24. The concentration effect in boiler emissions for isotopes of uranium, lead, and polonium has been incorporated into the calculations, using the factor of 5 discussed in Section IV-A. The emissions have been divided into the categories of dust, gases (radon), and particulates. The reason for this division is that dust emissions consist primarily of heavy particles that settle out quickly, resulting in exposures that are mainly occupational. Radon and particulate emission, however, will be carried far from the plant site, resulting in general population exposures.

Even though the WESCO plan calls for burial of the ash in mined-out areas, other coal gasification plants operated at long distances from the mines may find this alternative uneconomical. Therefore, it is important to calculate the radon emission resulting from disposal of the ash on the surface. Using the same assumptions as in Section IV-A, a 30-year accumulation of ash from a 275-million-SCF/day facility operating at 90% capacity would occupy 1850 acres and emit a maximum (assuming 100% release) of 19 Ci/day of radon-222, or 10,300 μCi per acre per day, compared to the natural background rate of 150 μCi per acre per day.

As was mentioned in the discussion of radioactive emissions from coal-fired power plants, the disposal of coal ash, either on the surface or in mined-out areas, is a potential source of groundwater contamination. This problem will have to be examined on a site-by-site basis, however, due to varying disposal methods, soil conditions, rate of precipitation, and so on.

b. Coal Liquefaction

Detailed analyses of the operations of [Ref. 60] and pollutant emissions from [Ref. 37] the H-Coal process have been carried out for two different types of coal--Illinois bituminous, and Powder River subbituminous. The calculation of radiological effects from coal liquefaction will be based on these analyses.

An H-Coal plant producing 100,000 bbl/day of synthetic crude oil will consume 55,177 tons/day of Powder River coal, with 4807 tons of this amount consumed in steam boilers, and 2717 tons consumed in the coal dryer. The remaining 47,653 tons is pulverized, dried, and fed to the liquefaction facility. It is assumed that all the radon contained in the coal entering the plant is released during either pulverization of the liquefaction feed coal or combustion of the coal used as fuel.

TABLE 26. RADIONUCLIDE EMISSIONS TO THE AIR FROM A 275 MILLION STANDARD CUBIC FEET PER DAY COAL GASIFICATION FACILITY USING NAVAJO COAL
(μCi/day)

Radionuclides	Dust	Gases	Particulates
Uranium-238	0.006		6.0
Thorium-234	0.006		1.2
Protactinium-234	0.006		1.2
Uranium-234	0.006		6.0
Thorium-230	0.006		1.2
Radium-226	0.006		1.2
Radon-222	--	6,200	--
Polonium-218	0.006		6.0
Lead-214	0.006		6.0
Bismuth-214	0.006		1.2
Polonium-214	0.006		1.2
Lead-210	0.006		6.0
Bismuth-210	0.006		1.2
Polonium-210	0.006		6.0
Thorium-232	0.008		1.6
Radium-228	0.008		1.6
Actinium-228	0.008		1.6
Thorium-228	0.008		1.6
Radium-224	0.008		1.6
Radon-220	--	8,100	--
Polonium-216	0.008		1.6
Lead-212	0.008		8.0
Bismuth-212	0.008		1.6
Polonium-212	0.005		1.0
Thallium-208	0.003		0.6
Potassium-40	0.011		2.4
Total	0.16	14,300	68

The other major sources of radionuclide releases to the air are the emission of particulate matter from the steam boilers and coal dryer, and the emission of coal dust from the coal dryer. All of these facilities are assumed to have controls on particulate emissions. The furnaces for the coal dryer and steam boilers are equipped with electrostatic precipitators which remove 99.5% of the particulate matter, resulting in the emission of 0.63 and 1.1 tons/day of particulates, respectively. The emission of coal dust from the dryer is 99% controlled by cyclones and a venturi scrubber, resulting in the emission of 6 tons/day of coal dust. In addition to these sources, about 0.68 tons/day of particulate matter is emitted as a result of the combustion of hydrocarbon gases derived from the liquefaction process. This material is assumed to consist primarily of coal ash. The releases of radionuclides from the above sources are shown in Table 25.

About 1.2 million gallons/day of waste water are generated in the coal hydrogenation unit. This water is treated for the removal of hydrogen sulfide and ammonia and sent to biological treatment ponds for further purification. Any suspended solids, such as coal ash, in this waste water would be largely removed by such treatment. In water-poor regions of the west, the treated water would be recycled to the evaporative cooling towers where most of it would be evaporated, with the contaminated blowdown stream being discharged to evaporation ponds.

If not returned to the mine for burial, the 30-year ash pile would occupy 830 acres and emit a maximum of 20.9 Ci/day of radon-222, or 25,200 µCi/acre.

It is possible that a small amount of ash will appear in the syncrude product. This amount has not been quantified for the H-Coal process. However, based on the data for the SRC process for producing clean boiler fuel from coal [Ref. 41], the ash content is expected to be no greater than 0.1%. Thus, the uranium-238, thorium-232, and potassium-40 contents of the product would be no greater than 0.012, 0.032, and 0.0005 ppm, respectively.

In the production of synthetic crude oil from Illinois coal via the H-Coal process, 38,241 tons of coal are pulverized, dried, and fed to the liquefaction plant to produce 100,000 barrels of synthetic crude oil per day. The major difference, in terms of radionuclide emissions, between using Illinois and Powder River coal is that in the former case the production of byproduct hydrocarbon gases is sufficient to supply all the plant fuel needs without additional coal having to be burned.

The only emissions to the air are 1.0 tons/day of coal dust from the controlled (99.8%) coal dryer, and 1.2 tons/day of particulate matter from combustion of byproduct gases. All the radon in the feed coal can be assumed to be released during pulverization and drying. The resulting radionuclide emissions are shown in Table 26.

About 770,000 gallons/day of waste water will be produced in the coal hydrogenation unit. If the plant is located in the eastern United States, then this waste water will probably be discharged after suitable treatment as

TABLE 25. RADIONUCLIDE EMISSIONS TO THE AIR FROM A 100,000 BBL/DAY COAL-LIQUEFACTION FACILITY USING POWDER RIVER COAL
(µCi/day)

Radionuclide	Dust	Gases	Particulates
Uranium-238	0.84		15.0
Thorium-234	0.84		8.9
Protactinium-234	0.84		8.9
Uranium-234	0.84		15.0
Thorium-230	0.84		8.9
Radium-226	0.84		8.9
Radon-222	--	11,500	--
Polonium-218	0.84		15.0
Lead-214	0.84		15.0
Bismuth-214	0.84		8.9
Polonium-214	0.84		8.9
Lead-210	0.84		15.0
Bismuth-210	0.84		8.9
Polonium-210	0.84		15.0
Thorium-232	0.76		7.8
Radium-228	0.76		7.8
Actinium-228	0.76		7.8
Thorium-228	0.76		7.8
Radium-224	0.76		7.8
Radon-220	--	10,500	--
Polonium-216	0.76		7.8
Lead-212	0.76		30.0
Bismuth-212	0.76		7.8
Polonium-212	0.76		5.0
Thallium-208	0.27		2.8
Potassium-40	0.72		7.6
Total	18	22,000	170

TABLE 26. RADIONUCLIDE EMISSIONS TO THE AIR FROM A 100,000 BBL/DAY COAL-LIQUEFACTION FACILITY USING ILLINOIS COAL
(μCi/day)

Radionuclides	Dust	Gases	Particulates
Uranium-238	0.66		7.2
Thorium-234	0.66		7.2
Protactinium-234	0.66		7.2
Uranium-234	0.66		7.2
Thorium-230	0.66		7.2
Radium-226	0.66		7.2
Radon-222	--	25,300	--
Polonium-218	0.66		7.2
Lead-214	0.66		7.2
Bismuth-214	0.66		7.2
Polonium-214	0.66		7.2
Lead-210	0.66		7.2
Bismuth-210	0.66		7.2
Polonium-210	0.66		7.2
Thorium-232	0.21		2.3
Radium-228	0.21		2.3
Actinium-228	0.21		2.3
Thorium-228	0.21		2.3
Radium-224	0.21		2.3
Radon-220	--	7,900	--
Polonium-216	0.21		2.3
Lead-212	0.21		2.3
Bismuth-212	0.21		2.3
Polonium-212	0.13		1.5
Thallium-208	0.08		0.8
Potassium-40	1.1		12.0
Total	12	33,200	126

described previously. This treatment is capable of reducing the suspended solids concentration to low levels, on the order of 10 ppm. Assuming that coal ash is the sole constituent of the suspended solids component of the waste water, the total radioactive content of discharged waste water would be 1.2 pCi/l.

The 30-year ash pile from a 100,000-bbl/day plant would occupy 1060 acres and release a maximum of 45 Ci/day of radon-222, or 42,700 µCi per acre. The maximum concentrations of uranium-238, thorium-232, and potassium-40 in the synthetic crude oil product would be 0.020, 0.019, and 0.0016 ppm, respectively.

C. Oil Shale

The major attraction of oil shale development is the large quantity of resource potentially available for recovery. It is estimated that recoverable reserves of oil shale in Utah, Wyoming, and Colorado containing at least 30 gallons of kerogen per ton of shale, in beds at least 30 feet thick, can yield over 130 billion barrels of oil [Ref. 42]. This is 20 times the current annual U.S. consumption, and an amount equal to the total estimated conventional U.S. oil reserves. However, the cost of recovering this oil is high. On the average, 1.4 tons of shale must be mined, crushed, processed, and disposed of for each barrel of oil recovered. Thus, an oil shale plant producing 100,000 barrels of oil per day must handle 50 million tons of shale per year. This is ten times the amount of material mined in the largest underground coal mines now in operation.

1. Mining

It is anticipated that most of the oil shale lying in underground deposits will be mined by the room-and-pillar technique described earlier. With this method, about 60% of the resource in-place can be extracted and 40% is left in the form of pillars.

When oil shale lies in deposits near the surface, open pit mining can be carried out. The overburden is first stripped away and stored, then the shale is recovered, crushed, and retorted. After all the resource is removed from the mine area, the overburden is replaced, contoured, and revegetated. The feasibility of surface mining oil shale is determined by the overburden-to-resource ratio and the availability of an area for overburden storage.

2. Conversion

Conceptually, the technology for obtaining liquid hydrocarbons from oil shale is simple. The crushed shale is heated in a closed vessel (retort) to a temperature of 900°F or greater, at which point the kerogen (the organic portion of the oil shale) vaporizes and is separated from the solid inorganic portion of the rock. After retorting, the shale oil is upgraded by means of hydrotreating (chemically reacting with hydrogen) to yield a synthetic crude oil that is suitable for transport via pipeline and can be used as a refinery feedstock.

The various methods for retorting oil shale differ in the manner in which heat is generated and transferred to the shale. The simplest method is the Fischer assay technique in which heat from an external source is transferred to the shale through the wall of the retort. Any fuel may be used to supply the heat. Due to large capital and operating costs, this method is unsuitable for commercial development. However, it is commonly used on a laboratory scale to measure the kerogen content of the shale.

There are four additional methods for retorting oil shale; they are in various stages of development and have the potential for commercial application. These four methods are discussed in the following paragraphs.

a. Gas-to-Solids Heating/Internal Gas Combustion Method

In this method, crushed shale is fed to the top of a vertical retort and low-Btu byproduct gas is injected at the bottom. The gas is combusted in the retort along with residual carbon on the spent shale, and the hot combustion gases heat the shale, driving off the oil vapors that are condensed at the top of the retort. The noncondensible gases are recycled for combustion. Due to the lack of external heating equipment, this method is less costly than other types of retorts. Energy recovery efficiency is somewhat lower, however.

The Union Oil Company version of the process uses a unique "rock pump" that injects shale at the bottom of the retort while combustion gases are drawn down from the top by blowers, and retorted shale oil is collected at the bottom. An advanced version of this retort, called the steam gas recirculation (SGR) process, was recently announced, and a 1500-ton/day demonstration plant based on this process will be built on private land in Colorado.

Another variation on the process has been constructed by Development Engineering, Inc. (DEI), the operating arm of Paraho Development Corporation (a consortium of 17 firms). This process, usually referred to as the Paraho retort, uses patented shale feed and spent shale discharge grates, which provide a uniform flow of shale through the retort. Multilevel gas injectors are also used to carefully control the level of incoming gases. DEI has completed a successful run on its 500-ton-per-day test plant near Rifle, Colorado, as part of a 30-month R&D program. Paraho has also proposed the construction and testing of a commercial-size retort on the Naval Oil Shale Reserve in Colorado. Both of the planned commercial operations on federally leased tracts in Utah have proposed using the Paraho retort.

b. Gas-to-Solids Heating/External Heat Generation Method

In this method, recirculated byproduct gas is used as the medium of heat transfer; however, heating of the gas is carried out in an external furnace, rather than by combusting the gas and spent shale within the retort. Some of the byproduct gas, carbon residue on the spent shale, or any other suitable fuel may be combusted to supply heat to the furnace. Paraho will soon begin testing a version of its retort which operates with externally heated gases.

The Union Oil SGR retort mentioned earlier is actually an example of the external heat generation method, although the original Union Oil technology was based on internal gas combustion.

c. In-Situ Retorting

In this process, shale rock is fractured in place by explosives to form an underground retorting chamber. Air is injected to combust part of the shale, and retorting is carried out by heat transfer from the hot combustion gases. Shale oil is collected from a hollow mined at the bottom of the shale column.

Numerous tests of this method have been made by various companies. Commercial feasibility has not yet been demonstrated, although recent tests by Garrett Research and Development, a subsidiary of Occidental Petroleum, appear promising. If the Garrett or other tests demonstrate the commercial feasibility of in-situ retorting, the use of this method could considerably reduce water consumption, spent shale disposal, and other problems presently associated with aboveground retorting. However, new problems, such as surface subsidence and the release of large quantities of combustion gases, would be created, and these would need to be carefully managed. This method is expected to be less costly than any above-ground retorting technique.

d. Hot Solids or Solids-to-Solids Heating Method

The TOSCO II process developed by The Oil Shale Corporation (TOSCO) is the most advanced version of this technique. In this process, ceramic balls are heated by the combustion of byproduct gases and liquids and transferred to the retort where they are mixed with crushed, preheated shale. Shale oil vapor is driven off and recovered. The ceramic balls are separated from the spent shale (on the basis of size) and subsequently reheated. A high efficiency of energy recovery is achieved; however, capital and operating costs are high.

The TOSCO II process is essentially ready for commercial application. Colony Development Operation (a joint venture of ARCO, Ashland, Shell, and The Oil Shale Corporation) has successfully completed tests on a 25-ton/day test unit and an 1100-ton/day semiworks plant at Parachute Creek, Colorado. Colony had announced plans to begin construction in April 1975, of a 50,000-bbl/day commercial plant based on the TOSCO II process. These plans were later postponed, with Colony citing rapidly inflating construction costs and uncertainties in U.S. energy policy as the basis for its decision.

There are several other planned commercial operations in which the TOSCO II retort will be used. These include the following: a 50,000-bbl/day plant planned by ARCO, TOSCO, Ashland, and Shell as a joint venture on Colorado Tract C-b; the Rio Blanco Oil Shale Project, a joint venture on Colorado Tract C-a by Gulf Oil and Standard of Indiana; and the 75,000-bbl/day Sand Wash Project in Utah planned by TOSCO.

The TOSCO II process is the most advanced retorting method for which a sufficient amount of information is available to provide the emission factors required for analysis. Thus, we have chosen to use it in our analysis of oil shale conversion.

Subsequent to retorting, described previously, the shale-derived gases and liquids must be processed to remove sulfur and nitrogen, and produce a syncrude that is suitable as a refinery feedstock. The raw shale oil is separated into naphtha, gas oil, and residual fractions. The naphtha and gas oil are sent to separate hydrotreaters where they are upgraded and desulfurized. The residual oil is sent to the coker unit, where coke is produced along with additional naphtha and oil, which are sent to the hydrotreaters. During hydrogenation of the naphtha and gas oil, sulfur and nitrogen compounds are converted to hydrogen sulfide and ammonia, which are separated in the sour water waste stream and subsequently recovered as ammonia solution and elemental sulfur.

The hydrogenated naphtha and gas oil are recombined and leave the plant as synthetic crude oil or fuel oil. The high-Btu byproduct gases from the retort are purified to remove hydrogen sulfide and ammonia, and to remove uncondensed liquids (naphtha). All of these gases are then consumed on site, either as plant fuel to provide steam and heat, or as feed to the steam reforming furnaces, where they are reacted to form hydrogen for the hydrotreaters.

3. People

The mining, retorting, and upgrading of oil shale must be considered to be part of a single integrated operation. This is because it is far too costly to ship the raw shale any significant distance from the mine, and the retorted shale oil is too viscous to be shipped by pipeline to be upgraded elsewhere. Therefore, these operations will be carried out at or near a single site. The sites will be located primarily in the oil shale-rich Piceance Basin in northwestern Colorado, although some development will take place in northeastern Utah as well.

Colony Development Operation has estimated that a 50,000-bbl/day oil shale mining retorting and upgrading operation will employ 900 to 1000 people [Ref. 44]. A 100,000-bbl/day operation, which is the unit size analyzed in the next section, would probably employ something less than twice this number, or 1600 to 1800 people.

4. Radiological Aspects

The emissions of radionuclides from oil shale mining, retorting and upgrading are calculated in the same manner as for coal conversion technologies, and depend on the radionuclide content of the resource as well as the emission of dust and particulate matter during conversion operations. The basic data on the emissions of various kinds was taken from the Environmental Impact Statement by the Bureau of Land Management for Colony Development Operation's proposed oil shale facility in Colorado [Ref. 44].

The uranium, thorium, and potassium concentrations in spent (retorted) shale have been measured at 0.99 ppm, 0.77 ppm, and 2.72%, respectively [Ref. 44]. Allowing for the fact that the mineral matter content of raw oil shale of 35-gallon/ton grade (which would be used in the Colony project) is 82.6%, and assuming that all uranium, thorium, and potassium remain in the spent shale during retorting, the uranium-238, thorium-232, and potassium-40 concentrations in raw oil shale would be 0.82, 0.64, and 2.7 ppm, respectively.

To support a 100,000-bbl/day oil shale facility, approximately 132,000 tons of raw shale would have to be mined, crushed, and retorted daily. It can be assumed that all the radon trapped in the shale is released to the atmosphere during these processes. The radon released into the closed retort would be withdrawn along with the byproduct retort gases, and would be later released when these gases are burned as plant fuel.

The emission of raw shale dust will occur at several points around the processing area, including the mine vent, the primary and secondary crushers, the crushed shale storage area, and the conveyor transfer points. The control of dust release with fabric filters will result in the emission of 2.6 tons of raw shale dust per day.

The main sources of emission of fine particulate matter will be in the shale preheat system, spent shale moisturizer, and the elutriator system. In these areas, fine shale particles, along with hot gases, are mobilized and vented from stacks controlled by venturi scrubbers. This process results in the emission of 18.7 tons/day of particulate matter. In addition, the combustion of byproduct hydrocarbon gases and liquids as fuels in various sections of the operation will result in the emission of 0.50 tons/day of particulate matter, for a total of 19.3 tons/day. All of this particulate matter may be assumed to have the composition of raw shale.

The emission of radionuclides to the air resulting from the processes discussed above are shown in Table 27.

All of the waste water generated in the oil shale operation will be treated and reused on the site. No discharges to streams or rivers are planned. This probably will be the case for all oil shale operations due to the scarcity of water in the western Colorado region, and the resulting necessity of making full use of the water that is available.

Approximately 113,000 tons of spent shale will be disposed of each day. This material will be dumped into canyons, compacted and graded, and ultimately revegetated. Due to the similarity of this material to the composition of the rock and soil of the surrounding area, it is probable that very little additional radon emanation above that of the natural background of the area will be induced by spent shale disposal operations.

Although saline runoff and leaching of salts from spent shale disposal piles present potentially serious environmental hazards, the low levels of radionuclides in these piles compared to those of neighboring soils should not result in significant activity levels in the runoff and leachate.

TABLE 27. RADIONUCLIDE EMISSIONS TO THE AIR FROM A 100,000 BBL/DAY OIL SHALE MINING, RETORTING, AND UPGRADING OPERATION (μCi/day)

Radionuclides	Dust	Gases	Particulates
Uranium-238	0.66		4.9
Thorium-234	0.66		4.9
Protactinium-234	0.66		4.9
Uranium-234	0.66		4.9
Thorium-230	0.66		4.9
Radium-226	0.66		4.9
Radon-222	--	32,800	--
Polonium-218	0.66		4.9
Lead-214	0.66		4.9
Bismuth-214	0.66		4.9
Polonium-214	0.66		4.9
Lead-210	0.66		4.9
Bismuth-210	0.66		4.9
Polonium-210	0.66		4.9
Thorium-232	0.16		1.3
Radium-228	0.16		1.3
Actinium-228	0.16		1.3
Thorium-228	0.16		1.3
Radium-224	0.16		1.3
Radon-220	--	8,300	--
Polonium-216	0.16		1.3
Lead-212	0.16		1.3
Bismuth-212	0.16		1.3
Polonium-212	0.10		0.9
Thallium-208	0.06		0.6
Potassium-40	40		310.0
Total	50	41,100	385

The presence of some of the trace elements occurring in raw shale has been detected in the upgraded shale oil [Ref. 43]. The concentrations of these elements have not been quantitatively assessed, however. It is probable that uranium and thorium, if present in the shale oil product, would be found only in very small concentrations--less than 0.1 ppm.

D. Geothermal Energy Systems

1. Introduction

The principal present commercial use of geothermal energy is the production of electricity at The Geysers in California [Ref. 29,45]. Current production capacity is approximately 502 MWe from 11 units, and four additional units totaling 415 MWe are in the process of being approved or constructed. This geothermal resource consists of dry steam, and has been estimated by various sources to have an ultimate capacity ranging from 2000 to 10,000 MWe. A reliable estimate of the extent of this resource is not available.

In addition to power generation, hot water resources are used for space heating at Klamath Falls, Oregon, and Boise, Idaho. Additional uses now under consideration include the desalination of water and food processing.

Geothermal resources may consist of dry steam, hot water, or a mixture of the two depending on pressure and temperature conditions at the wellhead. Resources are also classed according to the descriptions: hydrothermal, geopressured, and hot rock. Hydrothermal reservoirs consist of a permeable formation containing water and overlying a magma deposit. The molten rock furnishes heat to the groundwater in the formation, and the heated water or steam commonly appears naturally at the surface in the form of a hot spring or fumarole. The formation may be recharged periodically with rainfall.

The heat in geopressured resources results when the clays in a rapidly subsiding area trap heat in underlying permeable formations containing water. In hot rock systems, no permeable formation overlies the heat source. Consequently, the rock must be fractured and water injected to recover heat. Most geothermal resources are in the western third of the country.

Because neither the geopressured nor the hot rock systems have been exploited, no direct data are available on radioactive elements that may be contained in the geothermal fluids. Until such data are available, experience and data on hydrothermal systems may serve as an indicator of the potential radioactivity in these fluids.

The fate of any radioactive contaminants in the geothermal fluids will depend on their ultimate disposition. Because many fluids under consideration contain other contaminants that may be harmful to the environment, reinjection of the fluid into the formation is considered. The feasibility of this step has to be established for each formation. Consequently, the ultimate disposition of spent geothermal fluids cannot be determined. In the absence of specific process plans, it may be assumed that any water-borne contaminants produced would be discharged into surface waters, and that any gases produced would be discharged into the atmosphere. For example, in some present space heating applications, the water is discharged into the city storm sewer system. On the other hand, the present practice at The Geysers is an example of the likely fate of radioactive contaminants released in the generation of electricity from dry steam resources.

In the sections that follow, the energy system specifically described will be an electric power plant. Many of the steps in the use of geothermal power for electricity will apply equally to other applications. The major functional difference is that a heat exchanger would typically replace the turbine and condenser.

2. Exploration and Development

The exploration and development of geothermal resources resemble to a large degree similar phases for petroleum or natural gas resources [Ref. 29, 43]. The various techniques for determining the location, size, quality, density, and extent of geothermal resources will not be described in detail, since radiation exposure from these activities is negligible in comparison to activities involving very large quantities of geothermal fluids. Briefly, test corings, electrical conductivity tests, thermal gradient surveys, surface water analysis, seismic measurements, gravity and magnetic surveys are examples of geothermal exploration activities. However, little direct knowledge of thermal reservoir characteristics is obtainable without drilling, once a reservoir is located.

The extraction system for geothermal fluids is similar to that for oil and gas in that a well is drilled to sufficient depth, and is cased and completed to provide a safe and stable conduit for the fluid. However, there are several differences in details.

Once a well is completed, it may be tested at relatively high flow rates in order to establish the productivity and suitability of the well for commercial use.

After a steam well is completed and tested, a period of several years may intervene before it is put into production, because of construction and other delays. During this period it is slowly bled to prevent condensation and the accumulation of noncondensible gases. This bleed rate is negligible compared to production flow rates.

Geothermal wells may experience blowouts, which occur at the wellhead during drilling, or below the surface where the well intersects a permeable channel. Blowouts are controlled with blowout preventers at the wellhead and with the installation of suitable casing and cement fill in permeable zones. The possibility of a blowout is greatest early in the exploration phase when least is known of subsurface conditions. When a well is blowing out of control, especially near the surface, flow rates may approach production levels.

3. Production

If a suitable number of proven and tested wells are established in a sufficiently small area, it will be economic to construct pipelines connecting these wells to a facility that can absorb the thermal load and produce the desired output. In considering radiological hazards, it is unimportant whether the geothermal fluids are channeled through heat exchangers to provide space heating, process drying, or electricity generation in a binary (two fluid) cycle process, or through a turbine and condenser to generate electricity. The controlling feature will be the disposition of the geothermal fluids after the heat has been extracted.

An electric generating plant uses low pressure turbines. The resource at The Geysers, dry steam, is characterized as 350°F (177°C) and about 100 psi ($6.9x10^5$ Pa). This compares to 1000°F (538°C) and 3,500 psi ($2.4x10^7$ Pa) in a modern fossil fuel plant. Consequently, overall efficiency is down to about 15%, compared to 35 to 38% for the fossil fuel plant. In other terms, the heat rate is about 22,000 Btu ($2.32x10^7$ J) per kWhe instead of about 10,000 Btu. This implies that the now standard 55-MW generators each require about one million pounds of steam per hour. About seven wells, averaging about 150,000 pounds per hour, are required to produce this output.

If a unit goes out of production for short periods, the steam is vented for operational reasons, rather than closed off at the wells. Consequently, the flow of geothermal fluids is approximately constant regardless of electricity production. During venting, the entire flow with all contaminants is injected directly into the atmosphere at a site near the power plant.

During normal production, the steam flows in large pipes, to minimize the pressure drop, from the wells to the turbine inlet. Centrifugal separators in the lines near the well remove particulate matter that would exacerbate erosion of the turbine blades. Present units at The Geysers have direct contact condensers. The condensate is cycled through cooling towers and returned to the condensers or reinjected. Approximately 80% of the fluids produced are evaporated in the cooling process, and the remaining 20% are reinjected into the reservoir. Future units will use surface condensers to facilitate control of the hydrogen sulfide. The proportions of the fluids evaporated, however, would not materially change.

In the present units, which have direct contact condensers, noncondensible gases present in the steam are removed with gas ejectors that exhaust to the atmosphere. The relatively small quantities that remain in solution in the condensate and are not stripped out in the cooling tower cycle would be reinjected. In effect, essentially all the noncondensibles are emitted into the atmosphere. In two of the present Geysers units, experimental hydrogen sulfide control systems are installed. In these units, the gas ejectors vent into the cooling towers, where an hydrogen sulfide absorber is added to the cooling water circuit. Other noncondensibles continue to be emitted. In future units, the gas ejector stream will be treated in a Stretford unit to control the hydrogen sulfide. About 10% of the hydrogen sulfide might remain in the condensate, and be stripped out in the cooling tower unless plans to treat the condensate are altered. In summary, any gases present in the steam, other than hydrogen sulfide, and up in the atmosphere. They are emitted by the gas ejectors or the cooling tower. A very small amount remaining in solution would be reinjected into the reservoir.

Power plants that may be constructed to exploit hot water resources, such as in the Imperial Valley in California, would differ from The Geysers in several respects. In one scheme, depending on pressure and temperature conditions at the wellhead, the geothermal fluids would flash into a mixture of water and steam, perhaps in two or more stages depending on design. A typical Imperial Valley well might have a mass flow rate three times as high as a Geysers well, but less than a third would flash to steam at, say, 70 psi. Overall plant efficiency might be 11%, compared to 15% at The Geysers. Due to the very high dissolved-solids content (250,000 ppm), and other reasons such as land subsidence, it would be desirable to reinject the water. However, the feasibility of reinjection over long periods remains to be proven. In any event, if experience at The Geysers is indicative, noncondensible gases would be emitted to the atmosphere. Alternatively, a binary cycle process may be used with hot water resources. Again, the disposition of the spent fluid is the critical factor.

4. Radiological Aspects

The only radionuclide of interest in dry steam resources is radon-222 [Ref. 46, 47]. An average value for producing wells at The Geysers is 20,000 pCi per liter of condensed steam [Ref. 47]. For the standard 55-MW generating plant and the conditions described above, the radon release would be 0.24 Ci/day, or 4.4 Ci/1000 MW-day. Put another way, the release for a 55-MW plant is equivalent to the natural release of radon from about 2.7 square miles ($7 \times 10^6 m^2$) of land surrounding The Geysers [Ref. 47]. Samples of the ambient air around present power plants and developmental fields have been measured for radon content, and compare with normal levels found over the continental land area [Ref. 47].

Hot water resources vary widely in radionuclide content, but 136 sites throughout the western United States have been recently [Ref. 48] sampled for six nuclides--radon-222, radium-226, uranium-234 and -238, and thorium-230 and -232. Generally, the content of radon in pCi/l was at least an order of magnitude larger than those of the other nuclides. The importance of the other nuclides would depend on the disposal plans for the waste water--specifically, on the opportunity for the nuclides to accumulate selectively. It is difficult to speculate on this issue, since disposal is already a problem because of the high concentrations of dissolved solids. In addition, large scale development of any of the sampled reservoirs could easily change the indicated concentrations.

The highest concentrations of radon were measured in the Imperial Valley of California, an extensive area likely to undergo development sooner than most. The concentrations there ranged up to 14,000 pCi/l. If this figure is taken as representative for hot water resources, and we assume that essentially all of the radon separates into the flashed steam, then the radon released in the generation of electricity in a plant like The Geysers would be

17 Ci/1000 MW-day. Here, we have assumed that 25% of the hot water flashes to steam, and we have used the power plant efficiencies cited above. This radon emission rate would be nearly four times the rate at The Geysers for similar plant size and emission assumptions.

Estimates of emission rates for other applications of hot water resources depend directly on the assumed or planned fluid disposal practice. If closed cycle containment and 100% reinjection can be demonstrated and maintained for a site, emissions would be nil.

E. Nuclear Systems

The extraction of energy from nuclear fission involves several major processes, each of which could be the source of unacceptable releases of radioactive materials to the environment. The processes, referred to as the nuclear fuel cycle, include uranium mining, uranium milling, conversion to uranium hexafluoride, enrichment, fuel fabrication, reactor power plant operations, and fuel reprocessing. In addition, the nuclear system requires transportation services and has the problem of radioactive waste management. The throughput requirements of the nuclear fuel cycle and the associated radioactive materials generated depend on the combined efficiency of all the system components. For example, the mining requirements per unit quantity of electrical power output depends not only on the uranium content in the ore but also on the extraction efficiency of the mill, the thermal efficiency of the reactor, and so on. In general, the reported variations in these factors cause only minor quantitative differences in the analytical results. Therefore, for computational purposes the following typical values are used for light water reactors [Ref. 8,9,49].

- The U_3O_8 content in the uranium ore is 0.2%
- The mill extraction efficiency is 95%
- The conversion process loss is 0.25%
- The enrichment process loss is 0.05%
- The enriched uranium is 3.3% uranium-235
- The depleted uranium is 0.3% uranium-235
- The fuel fabrication process loss is 1%
- The uranium-235 fission energy output is 65%
- The plutonium fission energy output is 35%
- The thermal efficiency is 32.5%
- All the uranium-235 except process losses is recycled
- The reprocessing uranium loss is 1%.

The plutonium recovered in reprocessing is consigned for high temperature gas reactor (HTGR) and liquid metal fast breeder reactor (LMFBR) use. If the plutonium is recycled for light water reactor fuel, the uranium requirements will be fractionally decreased.

With regard to the use of natural thorium, thorium-232, in high temperature gas reactors to produce fissile uranium-233 as a nuclear fuel, the processes and problems associated with thorium-232 are similar to those of uranium-238; the differences are generally quantitative only. For example, the thorium content in thorium ores varies widely but is generally on the order of a few percent, that is, about an order of magnitude higher than the uranium content in uranium ore. The radioactivity associated with thorium-232 is also only half as much as that associated with uranium-238. Because the uranium-233 produced must be extracted through fuel reprocessing prior to use, it is anticipated that the use of thorium in the next few decades will be minimal compared with the use of uranium.

1. Uranium Mining

The Colorado Plateau (Arizona, Colorado, New Mexico, and Utah), is the largest uranium source area containing approximately 54% of the resource [Ref. 50]. (Another publication has estimated the uranium in this area to be in excess of 90% of the United States total [Ref. 51].) An additional 42% is located in the basins of Wyoming and the coastal plains of Texas. Uranium mines are usually located in remote areas where the population density is about 2 to 4 people per square kilometer (5 to 10 people per square mile) [Ref. 51].

The uranium mining methods used in the United States are open pit mining and underground mining. Although underground mines currently far outnumber open pit mines, open pit mines generally have higher production capacities, and slightly more than half of the uranium produced is from open pit mines. This near equality in total output is not anticipated to change significantly in the future as about one-half of the uranium reserves is in shallow deposits suitable for open pit mining and about one-half is located deep underground where underground mining is more suitable. About 96% of the reasonably assured uranium is in sandstone deposits.

Both open pit and underground mine sizes vary over a wide range. The average capacity of operating open pit mines in the United States is about 1.5×10^8 kg of ore per year and the average capacity of operating underground mines is about 2×10^7 kg of ore per year. For comparison purposes, the ore requirements per 1000 MWe year (9.7×10^{15} J thermal equivalent) are 1.3×10^8 kg.

The overburden for open pit mines varies but for calculative purposes it is estimated at 30 kg per kilogram of ore. The ore is sandstone and carnotite ($K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$). The total uranium content in 1.3×10^8 kg of ore is 2.2×10^5 kg (0.2% U_3O_8). The radioactivity of this amount of uranium and its daughters is 1040 Ci. Radionuclides other than uranium and its daughters are not reported, but the total activity for three likely major radionuclides (potassium-40, vanadium-50, and rubidium-87) is estimated to be relatively insignificant. The radioactive contents in the overburden are not reported but the total radioactivity for 3.9×10^9 kg of overburden is estimated as follows: 4.4 Ci of potassium-40, 7.4 mCi of rubidium-87, and insignificant vanadium-50.

The solid waste from underground mining is estimated to be about equal to the volume of the processed ore. The radioactivity associated with the solid waste is not reported. The water pumped from both open-pit and underground mines will contain dissolved and suspended uranium and its daughters. The radioactivity in the mine water is estimated at 1% of that in the ore, but it is merely returned to the mine by ion exchange as the water is permitted to seep through the soil.

The airborne radioactive effluents from uranium mines are particulates with uranium and daughter products and radon gas. The atmospheric releases of radioactivity from open-pit mining are not reported, but because dust is created and radon gas is released when the ore body is exposed and broken up by open-pit mining as in underground mining, the atmospheric releases by the two mining methods can be expected to be comparable. However, although the radon gas emitted from a 750-ton/day (6.8×10^5 kg/day) underground mine was calculated to be about 3 Ci/day [Ref. 52], open-pit mining atmospheric releases were estimated to be minimal [Ref. 51]. The radon released in open-pit mining has been estimated to be less than 0.01% of the total in the ore or about 7.5 mCi per 1.3×10^8 kg of ore. For the average sized open pit mine with a capacity of 1.5×10^9 kg per year, the radon release rate would be about 3 nCi/s. This may be compared to a calculated release rate of 20 μCi/s for an underground mine with the same capacity. The large discrepancy in the estimated radon releases bears investigation.

All the particulates in the effluent released to the atmosphere eventually return to the earth's surface. The radon gas decays to radon daughters and these eventually return to the earth's surface as particulates.

An open-pit mine area is restored for other use by covering the excavated area with the overburden that was previously removed. After restoration, radiological limitations on the future use of the area can be established by an assessment of its radiological state. The restoration of underground mine areas for other use includes the sealing of all access to underground areas. The accumulated waste-pile materials could be used for this purpose. Limitation on future use of the site can be established by radiological assessment.

2. Uranium Milling

The relatively low concentrations of uranium in the ore makes it economically imperative to minimize ore haulage distances; therefore, uranium mills are located near uranium mines in relatively sparsely populated areas. Mechanical and chemical processes are used to extract the uranium from the ore. The major features of a uranium mill are an ore storage area, an ore crushing building, an ore grinding building, chemical processing equipment including a solvent extraction building and leaching and precipitation tanks, a building for drying and packaging the output product, and a prepared location for receiving the mill waste. The problem of radiological controls exists throughout the entire milling process from ore storage to final product packaging and mill waste disposal.

At the ore storage site, small amounts of uranium and uranium daughter products in the form of dust and radon gas (mainly radon-222) are released to the atmosphere. The amounts released are small because most of the radioactive materials are bound within the individual pieces of ore. The ore is also wetted to control the dust. The milling process is initiated with the crushing and the grinding of the ore. Because the ore is still wet during crushing and the grinding is a wet process, the dust created by these processes is also minimal. Dust is also controlled by a dust collection system. The reduction of the ore to small particle sizes, however, permits an increased rate of radon gas release. The waste waters of these operations are piped to the retention pond. The chemical processes that follow (leaching, solvent extraction, precipitation, liquid removal, and calcining) all release radon to the atmosphere. The pulverizing and packaging operations also produce radioactive dust. Control measures are used to reduce the amount of radioactive dust escaping to the atmosphere.

The relative amounts of radioactive materials released by each milling process are not reported. The radon released during the entire milling operation is estimated to be between 20% and 80% of that in the ore. Most of the uranium and daughter products, other than radon, that escape to the atmosphere, do so during the drying process. Almost all of the other daughter products of uranium, in solution or as part of the mill tailings, are pumped to the retention pond. At the retention ponds, the solids settle, the liquid evaporates, and mill tailings piles are created. These mill tailings piles are the major sources of radioactive materials released to the environment from mill sites.

Uranium mill capacities vary widely. A mill output sufficient to supply the consumption requirements of five 1000-MWe reactors at 100% utilization or an output of 1.5 x 10^6 kg of yellowcake per year can be considered typical. As specified, the milling requirements per 1000 MWe-year (9.7 x 10^{16} J) of power is 1.3 x 10^8 kg of ore and the radioactivity of the uranium and uranium daughters in this ore is 1040 Ci. The milling process converts this input into the following outputs:

Yellowcake $(NH_4)_2U_2O_7$ or (85% U_3O_8)

Amount	2.9 x 10^5 kg
Uranium content	2.1 x 10^5 kg
Radioactivity	150 Ci (uranium-234, uranium-235, uranium-238)

Effluents: 890 Ci

Solids

Amount	1.29 x 10^8 kg
Radioactivity	810 Ci (uranium and uranium daughters)
Fate	Tailings pond

Liquids	
Amount	1.7 x 10^9 kg
Radioactivity	~4 Ci
Fate	Tailings pond
Airborne	
Amount	
Radon	~75 Ci
Uranium and uranium daughters	~2 Ci (mostly from dryer)
Fate	Return to earth

At the mill tailings site radon gas, radon-222, is formed from the decay of radium-226, which has a half-life of 1622 years. Radium-226 in turn is formed from thorium-230 and is in secular equilibrium with thorium-230, which has a half-life of 8 x 10^4 years. Because this half-life is extremely long relative to the tailings accumulation rate and the radon half-life of 3.8 days, the radon gas production rate at the tailings pile is essentially proportional to the amount of radium-226 or thorium-230 that is pumped to the tailings pile. The radon production rate at the tailings site will therefore increase with each day of mill operations, and the radon escaping from the tailings site can be expected to increase accordingly. After the cessation of mill operations the radon escape can be expected to remain relatively constant at the peak rate. It is estimated that about 5% of all the radon generated at the tailings site is released to the atmosphere [Ref. 8,12]. The radon gas then decays to its daughter products and is returned to earth with precipitation.

The rate of radon gas escape to the atmosphere from the tailings site of a 1.5 x 10^6 kg yellowcake mill after 10 years of operations is estimated to be about 6 μCi/s. Besides the airborne releases, radioactive materials in the liquid effluent at the mill tailings retention site could also make its way into the environment through seepage. Although the movement of radioactive material through seepage can be expected to be extremely slow, seepage surveillance is required to prevent unacceptable contamination of local water sources.

Radon-222 is not the only radon gas that is generated at the tailings site. A much smaller amount of radon-219, a daughter product originating from uranium-235, is also generated. If the uranium ore contains significant amounts of natural thorium, thorium-232, most of this thorium and its daughter products will also be pumped to the tailings pond. In this case, radon-220 is also generated at the tailing site and some of this radon will also escape to the atmosphere. The half-life of radon-220 is only 55 seconds, however, and the fraction escaping the tailings can be expected to be small. The radon-220 that escapes will quickly decay to stable lead.

3. Conversion to Uranium Hexafluoride

The yellowcake, packaged at the mill, is shipped to a conversion plant where the coarse U_3O_8 is converted to uranium hexafluoride, UF_6. Two different processes are used to produce UF_6. They are the "hydrofluor" process and the wet solvent extraction process. UF_6 conversion plants are currently located in low population density areas (5 to 10 people per square kilometer). A typical UF_6 conversion plant has a capacity of about 7 x 10^6 kg of UF_6 per year. This capacity is sufficient to produce 24,000 MWe-year of electrical energy (2.33 x 10^{18} J thermal energy equivalent).

The inputs to the conversion plant are new uranium in the form of yellowcake and recycled uranium in the chemical form $UO_2(NO_3)_2 \cdot 6H_2O$. The total uranium requirements per 1000 MWe-year are 2.1 x 10^5 kg of make-up uranium and 3.2 x 10^4 kg of recycle uranium. The radioactivity of this total amount of uranium is about 170 Ci. Because the uranium conversion loss is only 0.25%, all but about 0.4 Ci of the radioactivity is associated with the uranium converted to UF_6. Additional radioactive materials associated with the impurities of the coarse U_3O_8 inputs and the recycled uranium will also be part of the plant effluents. The radioactive solid effluent is buried and the liquids are pumped to storage ponds. A small fraction of the total radioactive effluents, about 0.01% of the throughput activity or about 0.016 Ci per 2.4 x 10^5 kg of uranium processed, is released to the atmosphere. This is equivalent to a release rate of about 11 nCi/s for the typical size conversion plant.

4. Uranium Enrichment

Enriched uranium fuel is required by light water reactors. The uranium-235 enrichment required is about 3%. Highly enriched uranium is required by high-temperature gas reactors for their initial fuel load. For this application and for the start-up of liquid metal fast breeder reactors the uranium-235 content in the total uranium is greater than 90%.

The uranium-235 enrichment method in use is isotopic separation by gaseous diffusion. Other technologies such as centrifuge separation and laser separation are being developed. The United States currently has three gaseous diffusion plants; one at Oak Ridge, Tennessee; one at Paducah, Kentucky; and one at Portsmouth, Ohio. The combined capacity of the three plants is about 1 x 10^7 kg of separative work units per year. This total capacity is equivalent to an input of about 3.2 x 10^7 kg of UF_6 and an output of 4.5 x 10^6 kg of 3.3% enriched UF_6 per year (sufficient to produce about 90,000 MWe-year of electrical energy from light water reactors or about 8.7 x 10^{18} J of thermal energy). Current plans are to increase the capacities of these plants by a factor of 2.5 by 1980 to meet projected domestic and foreign demands.

The enrichment process losses are estimated to be less than 0.05%. This is equivalent to about 0.085 Ci per 1000 MWe-year of uranium fuel processed. The total effluent radioactivity for all three enrichment plants operating at capacity can therefore be estimated at about 8 Ci per year.

The enrichment inputs per 1000 MWe-year fuel requirement are 3.55 x 10^5 kg of UF_6 with uranium contents as follows: 1.75 x 10^3 kg uranium-235, 135 kg uranium-236, and 2.4 x 10^5 kg uranium -238. The electrical energy consumed by the enrichment process per 1000 MWe-year fuel requirement is about 44 MWe-year. The outputs for the above inputs are 5.05 x 10^4 kg of enriched UF_6 with 1.13 x 10^3 kg of uranium-235 and 3.3 x 10^4 kg of uranium-238, and 3.05 x 10^5 kg of depleted UF_6 with 610 kg of uranium-235, 136 kg of uranium-236, and 2.05 x 10^5 kg of uranium-238. The enriched UF_6 is shipped to fuel fabrication and the depleted UF_6 is stored. The bulk of the radioactive effluents is discharged to holding ponds as a liquid and then discharged to streams. A small fraction of the effluent is airborne uranium and this is vented to the atmosphere. The total atmospheric release rate for all three plants operating at capacity is estimated at less than 25 nCi/s.

5. Fuel Fabrication

The fuel fabrication process converts the enriched UF_6 to complete fuel assemblies for reactor installation. The current industry includes plants that convert enriched UF_6 to UO_2 in either powder or pellet form, plants that use the UO_2 as input to produce completed fuel assemblies, and total process plants. The capacity of a relatively large fuel fabrication facility is on the order of 1 x 10^6 kg per year. The uranium losses for fuel fabrication from UF_6 conversion to the production of completed fuel assemblies are estimated at 1% of the total throughput uranium. About two thirds of the uranium losses are solid effluents that are buried within the plant site, and about one third is liquid and is discharged to a waste lagoon. The atmospheric releases of uranium are estimated to be about 0.003% of the total throughput uranium. Based on this percentage, the atmospheric releases for 1000 MWe-year of nuclear fuel are calculated to be about 400 µCi. The annual atmospheric releases for a plant with an annual throughput of 1 x 10^6 kg of uranium are calculated to about 0.4 nCi/s. All uranium effluent activity will be accompanied by the activity of the uranium daughter products thorium-231 and thorium-234.

With respect to the fabrication of plutonium and uranium-233 nuclear fuels, there has been only limited experience with plutonium and essentially no experience with uranium-233.

6. Reactor Operations

Up to the point of reactor operations, the radioactive materials of the nuclear fuel cycle are all of natural origin. If secular equilibrium between uranium and its daughters is assumed for the mined materials, then the radioactivity brought into the biosphere essentially remains at its original level, unless removed, even though each process and nature redistribute the individual radionuclides within the biosphere. Removal occurs through natural decay or by various control procedures, for example, encapsulation and burial. Because of the extremely long half-lives of the parent radionuclides--7.10 x 10^8 years for uranium -235 and 4.51 x 10^9 years for uranium-238--decay removal is negligible and the total disintegration rate of all the radionuclides is essentially constant.

This situation is changed with the initiation of reactor operations. Within the reactor, fissile materials are fissioned, fertile materials are converted to fissile materials, and lighter elements in the coolant and structural materials are made radioactive. The fissioning of the fissile materials, uranium-235 and plutonium-239 in light water reactors, uranium-235 and uranium-233 in high-temperature gas reactors, and plutonium-239 and plutonium-241 in breeder reactors, produces the reactor output energy. The fission process also produces fission products whose radioactivity is several orders of magnitude greater than that of the original fissile fuel. In the operation of nuclear reactors, some of these created radioactive materials are vented to the atmosphere and some are discharged to local waters, but most of the radioactive materials are contained within the fuel rods. After a period of operations during which most of the fissile materials are fissioned, the "spent fuel rods" are removed from the reactor, stored for a cooling period and shipped to a fuel reprocessing plant. The amount of radioactive pollutants released to the environment at the reactor site depends on a variety of factors. Such factors include the type and size of the reactor, reactor design, operations, percent of fuel failure, and the control measures used. Nuclear power plants are generally located not too distant from the communities they serve, where there is adequate cooling water, but population density in the immediate surroundings is generally low. Construction permits have been issued, however, for nuclear power plants at locations where the population density is high (Ref. 53).

The size of nuclear power plants coming on line, those under construction, and those planned for future installation are generally in the 800 MWe to 1200 MWe range. A 1000 MWe nuclear power plant can therefore be considered representative, and it will be used as the reference capacity for specifying the estimated radioactive effluents from nuclear reactors.

a. Light Water Reactors

Current nuclear power production is entirely from light water reactors and it is projected that light water reactors will continue to produce most of the nuclear power through the year 2000. The radioactive materials created in light water reactors are those created in the coolant water, those created in the structural materials, and those created within the fuel. The radioactive materials created in the coolant are generally gases, such as argon-41, fluorine-18, nitrogen-13, nitrogen-16, and oxygen-17. These radioactive gases all have relatively short half-lives and most of these radioactive materials are decayed in place. The portion that is released to the atmosphere with the discharge of gases from the coolant is quickly decayed to stable nuclides. Tritium is also created by neutron activation of boron-10, lithium-7, and deuterium, but the amount created is small when compared with that produced by fission. Other radioactive materials such as carbon-14 and sodium-24 are also created.

The radioactive materials created in the structural materials normally remain in the structural materials; small amounts do enter the coolant water. These radioactive materials include chromium-51, manganese-54, manganese-56, cobalt-58, cobalt-60, iron-59, nickel-63, copper-64, zinc-65, zirconium-95 and many others. Most of these relatively longlived radionuclides are normally removed from the coolant by the coolant purification system.

The radioactive materials created in the fuel are fission products and actinides. Most of these radioactive materials will remain in the uranium dioxide fuel pellets; however, the volatile radionuclides will diffuse from the fuel. These radioactive materials (and their daughter products) enter the coolant through defects in the fuel cladding. The nonvolatile radioactive materials are removed by the coolant purification system. The separation and storage of the gaseous and volatile materials, on the other hand, is difficult, and after a period of holdup to reduce radioactivity through the decay of the shorter half-life radionuclides, these gaseous and volatile materials are released to the atmosphere. The major radionuclides released to the environment are the gases: tritium, radiokrypton, and radioxenon; radioiodine, which is highly volatile at reactor temperatures; and carbon-14 as carbon dioxide.

Tritium is released to the environment as a liquid and as a gaseous effluent. The release rate of tritium from nuclear reactor operations has been variously estimated to be on the order of 100 Ci per 1000 MWe-year for boiling water reactors to 10,000 Ci per 1000 MWe-year for some pressurized water reactors [Ref. 9]. Roughly 90% of the material released is estimated to be released as a liquid effluent and roughly 10% in the form of tritiated gaseous water vapor is estimated to be released to the atmosphere although the partitioning of these releases vary and can be controlled. On the other hand, the estimated annual stack releases of tritium from Yankee Nuclear Power Station, a 185 MWe PWR, was only 13 Ci [Ref. 54].

The amount of krypton escaping to the coolant and subsequently released to the environment depends on the rate of krypton escape and the holdup time prior to release. The escape rate to the coolant is normally very slow, permitting substantial decay of the shorter half-life radiokryptons. In PWRs the gas volume buildup in the coolant is relatively slow, and consequently the extracted gases can be held up for a relatively long time (on the order of 30 days) prior to release. A 30-day delay would reduce all the short-lived radiokryptons to insignificance and only krypton-85, with a half-life of 10.76 years, would be released. The gas production rate in the BWR coolant, on the other hand, requires continuous removal and, because of its large volume, the delay time between gas removal and release must necessarily be shorter. Earlier practice had been to discharge these gases after only a short holdup time of about 30 minutes. The current holdup time for krypton from BWRs is about one day. A delay of one day would reduce krypton-89 to insignificance and the other short-lived radiokryptons by several orders of magnitude. The estimated krypton releases per 1000 MWe are on the order of 1 Ci per day for PWRs to about 100 Ci per day for BWRs [Ref. 9]. However, the estimated annual stack releases of krypton-85 from the Yankee Nuclear Power Station were only 3 Ci [Ref. 54].

The carbon-14, released as a gas from light water reactors, is that which is produced in the coolant. Without controls to capture the carbon containing substances in the off-gas, the estimated reactor carbon-14 releases are on the order of 6 Ci per 1000 MWe-year for PWRs and 16 Ci per 1000 MWe-year for BWRs [Ref. 55].

As with the case of radiokrypton, the amount of radioxenon escaping to the coolant and subsequently released to the environment depends on the rate of xenon escape and the holdup time prior to release. The escape rate to the coolant is normally very slow, permitting substantial decay of the shorter half-life radioxenon. The slow escape rate and the holdup times (15 to 30 days) results in xenon-133 being the only radioxenon released in significant quantities at the reactor site. The estimated reactor xenon releases per 1000 MWe are on the order of 20 Ci per day for PWRs and 130 Ci per day for BWRs [Ref. 9]. The estimated annual stack releases of xenon-133 from the Yankee Nuclear Power Station, however, were 0.1 Ci per year [Ref. 34].

The radioiodine that is released from nuclear reactors with coolant discharges also occurs as the result of fuel-cladding leaks and the fission of trace quantities of uranium in the coolant. Only small quantities of radioiodine, as gaseous and liquid effluent, are normally released at the reactor site. The estimated and measured releases of iodine-131 vary widely, but are in the order of several millicuries to several curies per 1000 MWe-year of power production.

Small quantities of other radionuclides are also released at the reactor site. These less volatile radionuclides are more amenable to decontamination and conversion to solid waste. The quantities released depend on the decontamination treatment used. The radionuclides that may be released in the liquid effluent in significant quantities besides tritium and iodine-131 are: chromium-51, manganese-54, iron-55, iron-59, cobalt-58, cobalt-60, strontium-89, yttrium-90, zirconium-95, niobium-95, molybdenum-99, ruthenium-103, ruthenium-106, cesium-134, cesium-137, barium-140, cerium-141, and cerium-144.

b. High-Temperature Gas Reactors

The use of a gas instead of water to cool the reactor core permits higher working temperatures. Helium is currently the gas used in HTGRs. At present there are only two HTGRs in the United States, a 40-MWe prototype and the Fort St. Vrain 330-MWe reactor. The latter plant is graphite moderated, helium cooled, and fueled with thorium and highly enriched uranium. The thermal efficiency of the plant is about 39%.

Plant operation is initiated with the fission of uranium-235, but as operations continue, the thorium-232 is converted to uranium-233 and an increasing fraction of the energy will result from the fission of uranium-233. As with the light water reactors, most of the radioactivity generated by the HTGR are the fission products. The distribution of the fission products from the fission of uranium-233 is not significantly different from that produced by the fission of uranium-235 or plutonium-239. Most of the fission products will remain in the fuel, but some can be expected to leak to the helium coolant. These are removed by the helium purifier and released to the environment under controlled conditions. A very small fraction of helium-3 in the helium is neutron activated to form tritium, and this is also released to the atmosphere. The major releases, however, are the gaseous fission products.

The radiokrypton releases are estimated at about 3000 Ci per 1000 MWe-year, and the radioxenon releases are estimated at about 100 Ci per 1000 MWe-year. Only small quantities of radioactive liquid wastes are generated by the HTGR, and these are decontaminated as necessary prior to discharge to the environment.

c. Liquid-Metal Fast Breeder Reactors

The fast breeder reactor uses liquid sodium for the primary coolant and plutonium and depleted uranium for fuel. It not only uses the uranium more efficiently in its own operations than do light water reactors but it also produces more fissionable materials than it uses. Because all but a small fraction of natural uranium is uranium-238, the LMFBR maximizes the use of the potential energy in uranium. Not only is enrichment unnecessary but the mining and milling requirements are considerably lower than those for light water reactors.

The fast breeder reactor program is still in a developmental stage, however, and only relatively low levels of LMFBR energy are projected in Scenarios III and V for the year 2000. Estimated radionuclide releases for the LMFBR also vary widely, but they are on the order of a magnitude or more lower than those estimated or measured for light water reactors.

7. Spent Fuel Reprocessing

The reprocessing of spent light water reactor fuels permits the maximum use of the scarce natural resource uranium-235. Because the recovered uranium is slightly enriched, about 0.8% uranium-235, reprocessing also decreases enrichment requirements. A small amount of fissile plutonium is also recovered. Spent fuel reprocessing is also the fuel recovery process for the thorium and plutonium fuel cycle, where the relatively plentiful resources thorium-232 and uranium-238 are converted to fissile uranium-233 and plutonium-239 in HTGRs and LMFBRs.

Currently, however, there is no spent fuel reprocessing plant in operation in the United States [Ref. 56]. The Nuclear Fuel Services Plant has been shut down for process alteration and expansion after 6 years of operation (1966 to 1972). Its capacity was 1000 kg of uranium per day. A second reprocessing plant, the Midwest Fuel Recovery Plant, was constructed but was never operational and is currently abandoned. The third and latest reprocessing plant, the Barnwell Nuclear Fuel Plant, was scheduled to be operational in 1976, but it has not been licensed to operate. This plant is designed to process 5000 kg of uranium per day. A plant this size has the capacity to service about forty-five 1000-MWe light water reactors.

After the fuel rods with the spent fuel are removed from the reactor, they are stored before they are shipped to reprocessing. A storage time of 150 days permits significant reduction of the radioactivity of the shorter half-life radionuclides. Even so, vast quantities of natural and reactor generated radioactive materials are present in the fuel rods at the time of reprocessing. The total radioactive effluents from fuel reprocessing is large when compared with the rest of the nuclear fuel cycle. The radioactive materials present in spent fuel are fission products, light element activation products, and the actinides. To recover the uranium, all these radioactive materials must be removed from the uranium. Plutonium is also recovered by chemical separation. The recovered uranium is converted to uranium hexafluoride and shipped to enrichment plants. The gaseous radionuclides and small amounts of the volatile radionuclides are released to the atmosphere. Other low level radioactive wastes are discharged to local waters. The remaining actinides, fission products, and the activated light elements, constituting the bulk of the radioactivity, are retained, converted to solids, and stored. Representative quantities of the radioactive materials in the spent fuel per 1000 MWe-year uranium reprocessing requirement (3.3 x 10^4 kg uranium) are listed in Table 28.

The Nuclear Fuel Service Plant, when in operation, released to the atmosphere all the krypton-85 and carbon-14, about 60% of the tritium, and minute quantities of radioiodine and other fission products and actinides in the spent fuel [Ref. 51]. The remainder of the tritium, small amounts of ruthenium-106, and other radioactive materials were released from the site as a liquid effluent. The radioactive effluents that will be released from future spent fuel reprocessing plants will depend upon the control systems used to limit these releases.

The estimated airborne radionuclide releases based on past experience per 1000 MWe-year of uranium processed are as follows [Ref. 51,55,56]:

Radionuclide	Ci/1000 MWe-yr
Krypton-85	3.4 x 10^5
Tritium	2.2 x 10^4
Carbon-14	10
Iodine-129	1 x 10^{-3}
Iodine-131	6 x 10^{-2}
Other fission products	0.9
Actinides	4 x 10^{-3}

The estimated liquid radionuclide releases to streams per 1000 MWe-year of uranium processed are as follows:

Radionuclide	Ci/1000 MWe-yr
Tritium	4 x 10^3
Ruthenium-106	4

TABLE 28. REPRESENTATIVE QUANTITIES OF RADIOACTIVE MATERIALS IN SPENT FUEL PER 1000 MWe-YEAR URANIUM REPROCESSING REQUIREMENT

Radionuclide	Curies (1000 MWe yr)	Radionuclide	Curies (1000 MWe yr)
Tritium	2.6×10^{4}	Cesium-135	39
Carbon-14	10	Cesium-137	3.4×10^{6}
Manganese-54	9.7×10^{5}	Cerium-141	2.6×10^{6}
Iron-55	6.5×10^{5}	Cerium-144	2.6×10^{7}
Iron-59	1.6×10^{4}	Pr.methium-147	6.5×10^{6}
Cobalt-58	9.7×10^{5}	Europium-155	1.3×10^{5}
Cobalt-60	6.5×10^{4}	Uranium-235	0.6
Krypton-58	3.4×10^{5}	Uranium-236	9
Strontium-89	3.2×10^{6}	Uranium-238	10
Strontium-90	1.9×10^{6}	Neptunium-237	15
Yttrium-91	6.1×10^{6}	Plutonium-238	1.3×10^{5}
Zirconium-93	65	Plutonium-239	1.6×10^{4}
Zirconium-95	1.3×10^{7}	Plutonium-240	2.1×10^{4}
Niobium-95	2.6×10^{7}	Plutonium-241	4.8×10^{6}
Technetium-99	480	Plutonium-242	65
Ruthenium-103	5.8×10^{6}	Americium-241	2.4×10^{4}
Ruthenium-106	2.6×10^{7}	Americium-243	650
Antimony-125	4.2×10^{5}	Curium-242	1.1×10^{6}
Tellurium-125m	2.1×10^{5}	Curium-244	6.5×10^{4}
Tellurium-127m	8.1×10^{5}		
Tellurium-129m	4.2×10^{5}		
Iodine-129	1.3		
Iodine-131	65		
Cesium-134	3.2×10^{6}		

The two newer and, as yet, inoperative plants are designed, however, to eliminate liquid-effluent discharges to the environment and all the tritium would be released to the atmosphere as a tritiated water vapor. The actual quantities of radioactive gaseous and liquid effluents that will be discharged to the environment once reprocessing operations are resumed will depend upon the control systems installed in the plants. Several decontamination systems are under development to reduce gaseous as well as particulate releases.

Except for that small fraction of the radioactive materials released to the environment, it is planned that the remainder will be converted to solids and these solids will eventually be consigned to perpetual storage. The current plans for this waste, that consist of about 1.3 x 10^8 Ci of fission products and 2 x 10^4 Ci of cladding hulls per 1000 MWe-year of energy produced, is to place it in interim storage for a few years and then to ship it to a repository for permanent storage. The problems associated with high level radioactive waste management are yet to be resolved, however, and a permanent disposal method has not been adopted.

V RADIOLOGICAL PROJECTIONS

A. Energy Scenario II Emissions and Effects

1. Coal

a. Mining and Preparation

The primary radionuclide emissions of concern during coal mining and coal preparation are the radon gases, radon-222 and radon-220. The radon release rates from these two activities are not known. To facilitate projections of annual releases and population exposure doses the following is assumed: (1) the combined mining and preparation operations release 20% of the radon in the coal, (2) the area source dose conversion factor applies, and (3) the average population within 80 km of these operations is 2×10^6 people.

The estimated radon release rates for all coal requirements are as follows:

Year	Ci/yr Radon-222	Radon-220	Total
1985	75	55	130
2000	135	99	234

The projected population exposure doses from the radon-222 releases are 1.7 man-rems per year in 1985 and 3 man-rems per year in 2000.

b. Direct Combustion for Electric Power

The primary radionuclides released to the environment in direct combustion of coal at electric power plants are uranium-238 and its daughters, thorium-232 and its daughters, and potassium-40. To facilitate projections of annual releases and population exposure doses, the following is assumed: (1) coal combustion releases all the radon in the coal, (2) 5% of the radon-222 generated from the radium-226 accumulated at the ash piles is released to the atmosphere, and (3) the average population within 80 km of coal-burning power plants is 4×10^6 people.

The estimated radioactive material releases are as follows:

Radionuclide	Ci/yr 1985	Ci/yr 2000
Stack releases		
Radon-222	190	230
Radon-220	160	200
Uranium-238	0.9	1.1
Uranium-238 + daughters	13	15
Thorium-232	0.7	0.8
Thorium-232 + daughters	6	7
Potassium-40	1.4	1.7
Ash pile releases		
Radon-222	6.5×10^3	1.9×10^4

The projected population exposure doses from the above releases are as follows:

Radionuclide	Man-Rems/Year 1985	Man-Rems/Year 2000
Radon-222	470	1.6×10^3
Uranium-238	40	48
Thorium-232	9	10
Potassium-40	6×10^{-3}	7×10^{-3}
Polonium-210	0.8	1

Additional exposure doses from uranium daughters and thorium daughters are not listed. Also, if the uranium concentration is increased by a factor of 5, then the resulting exposure doses will be correspondingly increased. Even if the uranium exposure doses were increased by a factor of 5, however, they would be over an order of magnitude lower than the radon exposure doses.

c. Gasification

The projected coal gasification energy levels for Scenarios II, IV, and V are the same and are at a relatively low level when compared to the levels projected for other energy systems. No coal gasification is projected for Scenario III. Using the data in Table 25, the projected radioactive material releases are as follows:

Radionuclides	Ci/yr	
	1985	2000
Stack releases		
Radon-222	15	57
Radon-220	30	75
Uranium-238	1.5×10^{-2}	5.5×10^{-2}
Uranium-238 + daughters	0.11	0.41
Thorium-232	4×10^{-3}	1.5×10^{-2}
Thorium-232 + daughters	2.8×10^{-2}	0.1
Potassium-40	6×10^{-3}	2.2×10^{-2}
Ash pile releases		
Radon-222	580	3,300

The projected population exposure doses using a local population of 2×10^5 people within 50 km of all gasification facilities are as follows:

Radionuclide	Man-Rems/Year	
	1985	2000
Radon-222	2	12
Uranium-238	3×10^{-2}	1×10^{-1}
Thorium-232	2×10^{-3}	9×10^{-3}
Polonium-210	7×10^{-4}	3×10^{-3}
Radium-226	7×10^{-3}	3×10^{-2}
Potassium-40	1×10^{-6}	4×10^{-6}

As in the case of direct coal combustion, additional doses from uranium and thorium daughters are not listed above. The sum of these exposure doses, however, will be small relative to the radon-222 exposure doses.

d. Liquefaction

The projected coal liquefaction energy levels for Scenarios II, IV, and V are the same. The projected energy level for 1985 is very low but for 2000 the projected level exceeds that of direct coal combustion for electrical power. No coal liquefaction is projected in Scenario III. Using an average of the emissions listed in Tables 26 and 27, the projected radioactive material releases are as follows:

Radionuclide	Ci/yr	
	1985	2000
Stack releases		
Radon-222	5×10^3	1.1×10^5
Radon-220	2.7×10^3	5.9×10^4
Uranium-238	5	110
Uranium-238 + daughters	46	1×10^3
Thorium-232	1.4	30
Thorium-232 + daughters	16	160
Potassium-40	--	--
Ash pile releases		
Radon-222	180	5,000

The projected population exposure doses assuming a local population of 2×10^5 people within 80 km of all liquefaction facilities are as follows:

Radionuclide	Man-Rems/Year	
	1985	2000
Radon-222	4	100
Uranium-238	11	240
Thorium-232	0.9	19
Polonium-210	0.2	5
Radium-226	5.5	120
Potassium-40	5.6×10^{-4}	1.2×10^{-2}

The uranium and thorium daughters not listed above will also provide exposure doses. The sum of these exposure doses could very well exceed the radon-222 exposure doses. As the ash piles accumulate with operations beyond the year 2000, however, radon-222 will be the major contributor to exposure doses.

2. Oil Shale

The primary radionuclide releases to the environment are those released to the atmosphere during processing. These radionuclides and their estimated release rates are listed in Table 27. The projected levels of shale oil utilization in Scenarios II, IV, and V are the same, i.e., 1 quad in 1985 and 8 quads in the year 2000. No shale oil utilization is projected in Scenario III.

For the projected utilization rates of Scenarios II, IV, and V, the calculated radionuclide releases are as follows:

Radionuclide	Ci/yr 1985	Ci/yr 2000
Uranium-238	1.9	15
Radon-222	1.3×10^4	1×10^5
All other uranium-238 daughters	25	200
Thorium-232	0.5	4.1
Radon-220	3.2×10^3	2.6×10^4
All other thorium-232 daughters	4	33
Potassium-40	120	970

To rank the relative importance of these emissions they need to be converted to radiation exposure doses. To do this, an exposed population is required and in this case a population of 80,000 is assumed to reside within 80 km of oil shale processing facilities. The calculated population exposure doses for the release rates listed above for the assumed population within 80 km of oil shale processing facilities are listed below for selected radionuclides.

Radionuclide	Man-Rems/Year 1985	Man-Rems/Year 2000
Radon-222	3.8	30
Radium-226	1.8	14
Uranium-238	1.7	13
Thorium-232	0.1	1
Polonium-210	3.5×10^{-2}	0.3
Potassium-40	9.6×10^{-3}	7.8×10^{-2}

3. Geothermal

The primary radionuclide of concern is the release of radon gas, principally radon-222, to the atmosphere. The fate of the other radionuclides in source fluid is dependent on the waste water disposal plan adopted. The level of geothermal utilization in Scenario II for 1985 and 2000 is extremely low when compared to the projections for other energy systems. Consequently, even though the radon release rates per unit of electric energy produced is relatively high, the annual projected releases are relatively low. For projection purposes, the radon release rates are estimated to range between 8,000 and 20,000 Ci per quad (10^{15} Btu). The projected releases for Scenario II are, therefore, 5,500 to 14,000 Ci per year in 1985 and 11,000 to 28,000 Ci per year in 2000.

To convert the radon release rates to population exposure doses, an exposed population is required. The assignment of an average population in the region of geothermal sites is difficult since only one site is currently being developed. For the purpose of this exercise a population of 1×10^6 people is assumed to be within 80 km of geothermal developments. Also because there are many atmospheric release points within a geothermal development area, the area source dose conversion factor is used. The projected population exposure doses are 100 to 250 man-rems per year in 1985, and 200 to 500 man-rems per year in 2000.

4. Nuclear Systems

a. Mining

The primary radionuclide emission of concern is the release of radon gas, principally radon-222, to the atmosphere. Based on the underground mining release rate of 574 Ci per ore requirement of 1.1×10^8 kg per 1000 MWe-year, the radon release rates of 2 mCi/s and 8 mCi/s are estimated for years 1985 and 2000, respectively. Because the half-life of radon-222 is only 3.8 days, it will decay through its even shorter half-life daughters to lead-210 rather rapidly. That is, all the radon-222 released to the environment would be decayed to lead-210 which in turn decays with a half-life of 22 years. Again, based on the underground mining release rate to the atmosphere, the radioactivity of the lead-210 distributed in the environment from the release of radon-222 is estimated at 150 Ci in 1985 and about 1100 Ci in the year 2000. It should be noted that the estimated radon releases associated with open-pit mining were several orders of magnitude lower than that for underground mining.

For ranking purposes, all radioactive emissions are converted to radiation exposure doses. The conversion requires an assumed exposed population. For uranium mining, a population of 80,000 people is assumed to reside within 80 km of all mining sites. Using this average population, the annual radon emission rates, and the area source conversion factor ($Q \times 1.8 \times 10^{-14}$), the population exposure doses of 90 man-rems/year and 360 man-rems/year are calculated for the years 1985 and 2000, respectively. It should be noted that the average individual exposure rate is not equal to the man-rems/year divided by 80,000, but is equal to the man-rems/year divided by 80,000 N, where N is equal to the number of mining sites.

b. Milling

The primary radionuclide emission of concern from the mill sites is the release of radon gas, principally radon-222, to the atmosphere. The sources of radon releases at the mill site are from the milling operations and from the mill tailings. Roughly half of the radon in the ore is released during mill operations and the remainder is discharged to the mill tailings pond. It is estimated that about 5% of the radon present in the pile escapes at the mill tailings and the remainder decays to daughter products within the pile. Because the shorter half-life radon-222 is continuously generated by the radium-226 in the tailings and 5% of this radon-222 is assumed to escape to the atmosphere, the radon-222 escape rate from all the mill tailings is estimated at 2,200 Ci/year in 1985 and 20,200 Ci/year in 2000. The radon escape rates from all milling operations are estimated at 4,400 Ci/year in 1985 and 16,500 Ci/year in 2000. The total radon release rates to the atmosphere from all milling sites are therefore estimated at 6,600 Ci/year in 1985 and 36,700 Ci/year in 2000. The released radon-222 decays to lead-210. The lead-210 activity in the environment created by the release of radon-222 is estimated at 11 Ci by 1985 and 110 Ci by 2000.

Assuming an exposed population of 80,000 people per mill site, the mill site radon releases convert to 10 man-rem/year in 1985 and 50 man-rem/year in 2000.

It was also estimated that less than 2 curies of uranium and uranium daughter radioactivity, besides radon, are released to the atmosphere per 1.3 x 10^8 kg of ore processed. This is equivalent to uranium and uranium daughter atmosphere release totals of about 200 Ci/year in 1985 and about 800 Ci/year in 2000. The total activity of the uranium and uranium daughters released to the environment is projected to be about 1000 Ci in 1985 and about 9000 Ci in 2000. In this case, because the uranium is released from a low-point source, the conversion factor in Ref. 8 was used. The uranium releases convert to 7000 man-rems/year and 28,000 man-rems/year for the years 1985 and 2000, respectively.

c. Conversion to Uranium Hexafluoride

In the conversion of yellowcake to uranium hexafluoride, it was estimated that about 0.017 Ci per 2.4 x 10^5 kg of uranium processed is released to the atmosphere. This projects to uranium release rates of about 2 Ci/year in 1985 and 7.5 Ci/year in 2000. The total activity of the uranium released is projected to be about 9.4 Ci in 1985 and 81 Ci in 2000. Because the half-lives of uranium-235 and uranium-238 are extremely long compared with their daughter products thorium-231 and thorium-234 respectively, insignificant daughter product radioactivity will be generated by the released uranium.

An average of 1.5×10^6 people are assumed to reside within 80 km of conversion facilities. Assuming this average population, the uranium emission rates convert to 1300 man-rems/year in 1985 and 5300 man-rems/year in 2000.

d. Uranium Enrichment

The estimated radioactive effluents from uranium enrichment amount to about 0.085 Ci of uranium per 1000-MWe light water reactor enrichment requirement. Of this amount, about 90% is discharged as a liquid to holding ponds and then subsequently discharged to streams. About 10% or less of the total radioactive effluents are estimated to be atmospheric releases. This projects to uranium release rates of 1 Ci/year in 1985 and 3.7 Ci/year in 2000. The total activity of the uranium released in the environment is estimated to be about 47 Ci in 1985 and 400 Ci in 2000.

Assuming an exposed population of 1.5×10^6 people per enrichment facility, the projected population exposures are 600 man-rems/year in 1985 and 2400 man-rems/year in 2000.

e. Fuel Fabrication

The uranium losses for fuel fabrication from uranium hexafluoride to the production of completed fuel assemblies are estimated at 1% of the total uranium throughput. About two-thirds are buried within the plant site as solids and about one-third is discharged as a liquid to a waste lagoon. About 0.003% of the total throughput uranium is released to the atmosphere. The projected atmospheric release rates from fuel fabrication are 0.05 Ci in 1985 and 0.2 Ci in 2000. The total activity of the atmospherically released uranium to the environment is estimated to be about 0.24 Ci in 1985 and 0.9 Ci in 2000.

Assuming an exposed population of 1.5×10^6 people per fuel fabrication facility, the projected population exposures are 30 man-rems/year in 1985 and 130 man-rems/year in 2000.

f. Reactor Operations

The major radioactive materials released from nuclear reactor sites are the fission products krypton-85 and xenon-133, which are noble gases and are released to the atmosphere, tritium which is released to local streams and to the atmosphere, and iodine-131 which is also released to the atmosphere. Small quantities of many other radionuclides are also released at the reactor site. The estimated radionuclide releases from reactor operations vary widely. The krypton-85 atmospheric releases are estimated at about 100 Ci per day for a 1000-MWe boiling water reactor (BWR) and 1 Ci per day for the pressurized water reactor (PWR); however, measured release rates equivalent to 15 Ci per year were reported for a BWR and 3 Ci per year were reported for a PWR. The xenon-133 atmospheric releases are estimated at about 130 Ci per day for a 1000-MWe BWR and 20 Ci per day for the PWR; however, measured release rates equivalent to 4.5 x 10^4 Ci per year were reported for a BWR and 0.5 Ci per year were reported for a PWR. The carbon-14 atmospheric releases are estimated at 16 Ci per year for a 1000-MWe BWR and 8 Ci per year for the PWR. The tritium atmospheric releases are estimated at 10 Ci per year for a 1000-MWe BWR and 1000 Ci per year for a PWR. The tritium releases as liquid effluent to streams are estimated at 90 Ci per year for the BWR and 9000 Ci per year for the PWR. The iodine-131 atmospheric releases are estimated to range from several millicuries to several curies per year.

The annual radioactive noble gas releases of a 1000-MWe high-temperature gas-cooled reactor (HTGR) are estimated at 3000 Ci for krypton-85 and 100 Ci for xenon-133. The annual releases from a 1000-MWe liquid-metal fast breeder reactor (LMFBR) are estimated to be considerably lower than the HTGR. Because the estimated rates for these reactor types are speculative and projected energy levels for them are relatively minimal, all projected reactor radioactive material releases will be based on BWR and PWR release rates.

Because the estimated radioactive releases are significantly different between the BWR and the PWR, the projected releases are based on estimated LWR installed capacities of 40% BWR and 60% PWR.

The projected krypton-85 release rates are 1.7 x 10^6 Ci per year in 1985 and 6.3 x 10^6 Ci per year in 2000. Because the half-life of krypton-85 is 10.76 years, a considerable buildup of the krypton-85 released to the environment will result. The total activity of the released krypton-85 is estimated at 7.1 x 10^6 Ci in 1985 and 4.7 x 10^7 Ci in 2000.

The projected xenon-133 release rates are 3.1 x 10^6 Ci per year in 1985 and 1.2 x 10^7 Ci per year in 2000. Because the half-life of xenon-133 is only 5.3 days, there will not be any buildup of xenon-133.

The projected carbon-14 atmospheric release rates are 1,200 Ci per year in 1985 and 4,400 Ci per year in 2000. Because the half-life of carbon-14 is 5700 years, a buildup of carbon-14 activity will result. The total activity of the released carbon-14 is estimated at 5,500 Ci in 1985 and 48,000 Ci in 2000.

The projected tritium atmospheric release rates are 7.1 x 10^4 Ci per year in 1985 and 2.7 x 10^5 Ci per year in 2000. The projected tritium stream release rates are 6.4 x 10^5 Ci per year in 1985 and 2.4 x 10^6 Ci per year in 2000. The projected total tritium release rates to the environment are 7.1 x 10^5 Ci per year in 1985 and 2.7 x 10^6 Ci per year in 2000. The tritium released to the atmosphere is in the form of water vapor and its residence time in the atmosphere is relatively short. The tritium half-life of 12.25 years is sufficiently long, however, for a considerable buildup of released tritium activity in the environment. The projected total activity of the released tritium is estimated at 3 x 10^6 Ci in 1985 and 2 x 10^7 Ci in 2000.

The projected iodine-131 atmospheric release rates are estimated at less than one curie to a few hundred curies per year in 1985, and from one to one thousand curies per year in 2000. Because of its relatively short half-life of 8 days, the buildup of iodine-131 with time is insignificant.

The population density near reactor sites varies widely; however, for calculative purposes an average of 4 x 10^6 people are assumed to reside within 80 km of nuclear power plants and an average of 80,000 people per plant consume downstream water. For macroregional effects, representative populations of 1.25 x 10^8 and 1.5 x 10^8 are assumed for the eastern part of the United States in 1985 and 2000, respectively. The projected population exposure doses from reactor operations in man-rems/year are as follows:

Radionuclide	Man-Rems/Year	
	1985	2000
Krypton-85 (local air)	14	52
Krypton-85 (macroregional)	1 x 10^{-8}	5 x 10^{-8}
Xenon-133 (local air)	25	96
Carbon-14 (local air)	0.02	0.09
Carbon-14 (macroregional)	0.2	0.9
Tritium (local air)	0.9	3
Tritium (local fallout)	70	280
Tritium (local water)	5,000	18,000
Tritium (macroregional)	440	2,000
Iodine-131 (local air)	5	17

8. Spent-Fuel Reprocessing

Currently there is no spent-fuel reprocessing facility in operation in the United States. Although the regulations governing future operations may be more stringent than those in the past, the releases of past operations are used for the projections that are listed below.

Radionuclide	Ci/yr	
	1985	2000
Atmospheric releases		
Krypton-85	4 x 10^7	1.5 x 10^8
Carbon-14	1,200	4,400
Tritium	2.6 x 10^6	1 x 10^7
Iodine-129	0.1	0.4
Other fission products	100	400
Actinides	0.5	2
Stream releases		
Tritium	4.7 x 10^5	1.76 x 10^6
Ruthenium-106	470	1,760

The total activity of the released krypton-85 is estimated at 1.7 x 10^8 Ci in 1985 and 1.1 x 10^9 in 2000. The total activity of the released carbon-14 is estimated at 5,500 Ci in 1985 and 48,000 Ci in 2000. The total activity of all the released tritium is estimated at 1.3 x 10^7 Ci in 1985 and 8.7 x 10^7 Ci in 2000. The ruthenium-106 has a half-life of 1 year and buildup of ruthenium-106 with time is minimal, that is, the ruthenium-106 activity for any year is approximately equal to the sum of the annual releases.

The population density near current inoperative facilities varies widely, and it is difficult to project the population densities near future facilities. For calculation purposes a population of 4 x 10^6 people is assumed to reside within 80 km of each facility, and 80,000 people per facility consume the downstream water.

The projected population exposure doses from reprocessing facility emissions in man-rems per year are as follows:

Radionuclide	Man-Rems/Year	
	1985	2000
Krypton-85 (local air)	320	1200
Krypton-85 (macroregional)	2.5 x 10^{-7}	1.1 x 10^{-6}
Carbon-14 (local air)	0.02	0.09
Carbon-14 (macroregional)	0.2	0.9
Tritium (local air)	50	190
Tritium (local fallout)	2700	10,000
Tritium (local water)	3500	14,000
Tritium (macroregional)	1.6 x 10^5	7.5 x 10^5
Iodine-129 (local air)	0.06	0.3
Iodine-131 (local air)	0.9	3
Ruthenium-106 (local water)	300	1300
Actinides (local air)	2	8

The radioactive waste materials that are not released to the environment are viewed as a source of potential radioactive environmental pollution. This waste management problem is yet to be completely resolved. Within the first few years, the decay of the radioactive waste can be expected to be relatively rapid. However, with the depletion of the shorter lived radionuclides, the decay rate will be relatively slow. The fission product activity of the nuclear waste produced is estimated at 1.5 x 10^{10} Ci per year in 1985 and 5.7 x 10^{10} Ci per year in 2000. The total activity of the accumulated waste fission products is estimated at 3 x 10^{10} Ci in 1985 and 1.4 x 10^{11} Ci in 2000. The estimated actinide activity produced is 2.4 x 10^6 Ci per year in 1985 and 9 x 10^6 Ci per year in 2000. The total accumulated actinide activity is estimated at 1 x 10^7 Ci by 1985 and 7 x 10^7 Ci by the year 2000.

E. Energy Scenario III Emissions and Effects

1. Coal

a. Mining and Preparation

In Scenario III, the coal mined is a fraction less in 1985 and about 40% less in the year 2000 than the amount mined in Scenario II. The amount used for direct combustion to produce electric power, however, is the same in 1985 and increased by about 20% in the year 2000, compared with Scenario II. The projected radon release rates for all coal requirements are as follows:

Year	Ci/yr Radon-222	 Radon-220	 Total
1985	68	50	118
2000	104	77	181

The projected population exposure doses from the radon-222 releases are 1.5 man-rem per year in 1985 and 2.3 man-rem per year in 2000.

b. Direct Combustion for Electric Power

The projected radioactive material releases are as follows:

Radionuclide	Ci/yr 1985	 2000
Stack releases		
Radon-222	190	280
Radon-220	160	240
Uranium-238	0.9	1.3
Uranium-238 + daughters	12	17
Thorium-232	0.7	1
Thorium-232 + daughters	8	13
Potassium-40	1.4	2.1
Ash pile releases		
Radon-222	6,500	2 × 10^4

The projected population exposure doses from the above releases are as follows:

Radionuclide	Man-Rems/Year 1985	 2000
Radon-222	470	1,400
Uranium-238	40	57
Thorium-232	9	1.2
Potassium-40	6×10^{-3}	8.4×10^{-3}
Polonium-210	0.8	1.1

c. Gasification

No coal gasification is projected in Scenario III.

d. Liquefaction

No coal liquefaction is projected in Scenario III.

2. Oil Shale

No shale oil is projected in Scenario III.

3. Geothermal

The projected geothermal developments in Scenario III are roughly twice that of Scenario II in 1985 and roughly 5 times that of Scenario II in 2000. Nevertheless, the projected geothermal energy levels are very low with respect to projected total energy levels. The projected radon releases from geothermal plants are 13,000 to 32,000 Ci per year in 1985 and 53,000 to 130,000 Ci per year in 2000.

The projected population exposure doses from these releases are 230 to 580 man-rems per year in 1985 and 950 to 2,300 man-rems per year in 2000.

4. Nuclear Systems

Of the four energy scenarios, the growth rate of the use of nuclear energy is fastest in Scenario III. Nevertheless, the growth rate of Scenario III is only 22% greater than that of Scenario II in 1985 and only 10% greater than that of Scenario II in the year 2000. The projected radioactive pollutants released to the environment will therefore be similarly increased.

a. Mining

The projected radon atmospheric release rates for the uranium mining requirements are about 2.6 mCi/s in 1985 and about 9 mCi/s in 2000. The amount of radioactivity from the lead-210, distributed in the environment from the radon-222 released, is estimated at about 170 Ci to 180 Ci by 1985 and about 1200 Ci by the year 2000.

The projected radon population exposure doses are 120 man-rems per year in 1985 and 410 man-rems per year in 2000.

b. Milling

The total radon-222 escape rates from milling operations and from the accumulated tailings piles are estimated at 7,900 Ci per year in 1985 and 40,590 Ci per year in 2000. The lead-210 activity in the environment created by the release of radon-222 from the mill site is estimated at about 13 Ci by 1985 and 120 Ci by the year 2000. The projected activity of the uranium released to the atmosphere is about 250 Ci per year in 1985 and about 900 Ci per year in the year 2000. The total activity of the uranium and uranium daughters released to the environment is estimated at about 1,200 Ci by 1985 and about 10,000 Ci by the year 2000.

The projected population exposure doses are 11 man-rems per year in 1985 and 70 man-rems per year in 2000 for radon; and 9,000 man-rems per year in 1985 and 32,000 man-rems per year in 2000 for uranium.

c. Conversion to Uranium Hexafluoride

The projected uranium release rates from the uranium conversion facilities are about 3 Ci per year in 1985 and about 8.2 Ci per year in the year 2000. The total activity of the uranium released is projected to be about 11 Ci by 1985 and about 52 Ci by the year 2000.

The project population exposure doses are 2,000 man-rems per year in 1985 and 5,400 man-rems per year in 2000.

d. Uranium Enrichment

The projected atmospheric releases of uranium from the uranium enrichment facilities are about 1 Ci per year in 1985 and about 4 Ci per year in the year 2000. The projected uranium releases to streams are about 11 Ci per year in 1985 and about 37 Ci per year in 2000. The total activity of the uranium released to the environment is estimated at 53 Ci by 1985 and 460 Ci by the year 2000.

The projected population exposure doses are 660 man-rems per year in 1985 and 2,600 man-rems per year in 2000.

e. Fuel Fabrication

The projected atmospheric release rates of uranium from fuel fabrication facilities are about 0.06 Ci per year in 1985 and 0.2 Ci per year in the year 2000. The total activity of the atmospherically released uranium is estimated at 0.29 Ci by 1985 and 2.1 Ci by the year 2000.

The projected population exposure doses are 40 man-rems per year in 1985 and 130 man-rems per year in 2000.

f. Reactor Operations

The projected krypton-85 release rates for reactor operations are estimated at 2×10^6 Ci per year in 1985 and 7×10^6 Ci per year in the year 2000. The total activity of the released krypton-85 is estimated at 8×10^6 Ci by 1985 and 5.3×10^7 Ci by the year 2000.

The projected xenon-133 release rates are 3.8×10^6 Ci per year in 1985 and 1.3×10^7 Ci per year in the year 2000.

The projected carbon-14 release rates are 1,400 Ci per year in 1985 and 4,800 Ci per year in 2000. The total activity of the released carbon-14 is estimated at 6,300 Ci in 1985 and 54,000 Ci in 2000.

The projected tritium atmospheric release rates are 8.7×10^5 Ci per year in 1985 and 3×10^6 Ci per year in the year 2000. The projected tritium stream release rates are 7.8×10^3 Ci per year in 1985 and 2.6×10^5 Ci per year in 2000. The projected total tritium release rates to the environment are 8.7×10^5 Ci per year in 1985 and 3×10^6 Ci per year in 2000. The projected total activity of the tritium releases is estimated at 3.4×10^6 Ci by 1985 and 2.3×10^7 Ci by the year 2000.

Because the range of the estimated iodine-131 release rates was extremely broad, the projected values are the same as those projected for Scenario II, that is, one curie to a few hundred curies per year in 1985, and one curie to one thousand curies per year in the year 2000.

The projected population exposure doses in man-rems per year are as follows:

Radionuclide	Man-Rems/Year 1985	Man-Rems/Year 2000
Krypton-85 (local air)	16	56
Krypton-85 (macroregional)	1.3 x 10^{-8}	5.3 x 10^{-8}
Xenon-133 (local air)	30	100
Carbon-14 (local air)	0.03	0.1
Carbon-14 (macroregional)	0.2	0.9
Tritium (local air)	1	4
Tritium (local fallout)	90	310
Tritium (local water)	6,000	20,000
Tritium (macroregional)	540	2,300
Iodine-131 (local air)	5	18

6. Spent-Fuel Reprocessing

The projected radionuclide releases of fuel reprocessing operations are as follows:

Radionuclide	Ci/yr 1985	Ci/yr 2000
Atmospheric releases		
Krypton-85	4.9 x 10^7	1.6 x 10^8
Carbon-14	1,400	4,800
Tritium	3.2 x 10^6	1.1 x 10^7
Iodine-129	0.14	0.5
Iodine-131	9	29
Other fission products	130	430
Actinides	0.6	2
Stream releases		
Tritium	5.8 x 10^5	1.9 x 10^6
Ruthenium-106	580	1,930

The total activity of the released krypton-85 is estimated at 2 x 10^8 Ci by 1985 and 1.2 x 10^9 Ci by the year 2000. The total activity of the released carbon-14 is estimated at 6,300 Ci in 1985 and 54,000 Ci in 2000. The total activity of all the released tritium is estimated at 1.5 x 10^7 Ci by 1985 and 9.8 x 10^7 Ci by the year 2000.

The projected population exposure doses in man-rems per year are as follows:

Radionuclide	Man-Rems/Year	
	1985	2000
Krypton-85 (local air)	390	1,300
Krypton-85 (macroregional)	3×10^{-7}	1.2×10^{-6}
Carbon-14 (local air)	0.03	0.1
Carbon-14 (macroregional)	0.2	0.9
Tritium (local air)	60	210
Tritium (local fallout)	3,300	11,000
Tritium (local water)	4,400	16,000
Tritium (macroregional)	7×10^{5}	8.3×10^{5}
Iodine-129 (local air)	0.09	0.3
Iodine-131 (local air)	1	4
Ruthenium-106 (local water)	370	1,200
Actinides (local air)	2.4	8

The projected production rates of the radioactive fission products that are not released to the environment are 1.9×10^{10} Ci per year in 1985 and 6.3×10^{10} Ci per year in the year 2000. The total activity of accumulated waste fission products is estimated at 3.6×10^{10} Ci by 1985 and 1.6×10^{11} Ci by the year 2000. The estimated actinide activity produced is 2.9×10^{6} Ci per year in 1985 and 9.7×10^{6} Ci per year in the year 2000. The total accumulated actinide activity is estimated at 1.1×10^{7} Ci by 1985 and 8×10^{7} Ci by the year 2000.

C. Energy Scenario IV Emissions and Effects

1. Coal

a. Mining and Preparation

In Scenario IV, the coal production in 1985 and 2000 is slightly lower than that of Scenari II. The amount of coal used for direct combustion electric power generation is also slightly lower. The projected radon release rates for all coal requirements are as follows:

Year	Ci/yr		
	Radon-222	Radon-220	Total
1985	64	47	111
2000	121	89	210

The projected population exposure doses from the radon-222 releases are 1.4 man-rems per year in 1985 and 7.7 man-rems per year in 2000.

b. Direct Combustion for Electric Power

The projected radioactive material releases are as follows:

Radionuclide	Ci/yr 1985	Ci/yr 2000
Stack releases		
Radon-222	174	209
Radon-220	147	176
Uranium-238	0.8	1
Uranium-238 + daughters	11	13
Thorium-232	0.6	0.7
Thorium-232 + daughters	5.5	6.6
Potassium-40	1.3	1.6
Ash pile releases		
Radon-222	6,000	1.7×10^5

The projected population exposure doses from the above releases are as follows:

Radionuclide	Man-Rems/Year 1985	Man-Rems/Year 2000
Radon-222	430	1,200
Uranium-238	35	44
Thorium-232	7	9
Potassium-40	5×10^{-3}	6×10^{-3}
Polonium-210	0.7	0.9

c. Gasification

The proposed coal gasification energy levels are the same as Scenario II. The projected radioactive material releases are as follows:

Radionuclide	Ci/yr 1985	Ci/yr 2000
Stack releases		
Radon-222	15	57
Radon-220	20	75
Uranium-238	1.5×10^{-2}	5.5×10^{-2}
Uranium-238 + daughters	0.11	0.41
Thorium-232	4×10^{-3}	1.5×10^{-2}
Thorium-232 + daughters	2.8×10^{-2}	0.1
Potassium-40	6×10^{-3}	2.2×10^{-2}
Ash pile releases		
Radon-222	580	3,300

The projected population exposure doses, assuming a local population of 2×10^{5} people within 80 km of all gasification facilities, are as follows:

Radionuclide	Man-Rems/Year 1985	Man-Rems/Year 2000
Radon-222	2	12
Uranium-238	3×10^{-2}	1×10^{-1}
Thorium-232	2×10^{-3}	9×10^{-3}
Polonium-210	7×10^{-4}	3×10^{-3}
Radium-226	7×10^{-3}	3×10^{-2}
Potassium-40	1×10^{-6}	4×10^{-6}

d. Liquefaction

The projected coal liquefaction energy levels are the same as Scenario II. The projected radioactive material releases are as follows:

Radionuclide	Ci/yr 1985	Ci/yr 2000
Stack releases		
Radon-222	5×10^{3}	1.1×10^{5}
Radon-220	2.7×10^{3}	5.9×10^{4}
Uranium-238	5	110
Uranium-238 + daughters	46	1×10^{3}

Radionuclide	Ci/yr 1985	Ci/yr 2000
Stack releases (continued)		
Thorium-232	1.4	30
Thorium-232 + daughters	16	160
Potassium-40	--	--
Ash pile releases		
Radon-222	180	5,000

The projected population exposure doses, assuming a local population of 2×10^5 people within 80 km of all liquefaction facilities, are as follows:

Radionuclide	Man-Rems/Year 1985	Man-Rems/Year 2000
Radon-222	4	100
Uranium-238	11	240
Thorium-232	0.9	19
Polonium-210	0.2	5
Radium-226	5.5	120
Potassium-40	5.6×10^{-4}	1.2×10^{-2}

2. Oil Shale

The projected shale oil energy levels are the same as Scenario II. The projected radioactive material releases to the atmosphere are as follows:

Radionuclide	Ci/yr 1985	Ci/yr 2000
Uranium-238	1.9	15
Radon-222	1.3×10^4	1×10^5
All other uranium-238 daughters	25	200
Thorium-232	0.5	4.1
Radon-220	3.2×10^3	2.6×10^4
All other thorium-232 daughters	4	33
Potassium-40	120	970

The projected population exposure doses, assuming a local population of 80,000 people within 80 km of all oil shale processing facilities, are as follows:

Radionuclide	Man-Rems/Year	
	1985	2000
Radon-222	3.8	30
Radium-226	1.8	14
Uranium-238	1.7	13
Thorium-232	0.1	1
Polonium-210	3.5×10^{-2}	0.3
Potassium-40	9.6×10^{-3}	7.8×10^{-2}

3. Geothermal

The geothermal development projected in Scenario IV is the highest of the four scenarios. The projected geothermal energy level of 15 quads (10^{15} Btu) per year for the year 2000 is roughly one-tenth of the total projected energy level for that year. The projected radon releases from geothermal plants are 2.6×10^4 to 6.4×10^4 Ci per year in 1985 and 1.2×10^5 to 3×10^5 Ci per year in 2000.

The projected population exposure doses are 470 to 1,200 man-rems per year in 1985 and 2.2×10^3 to 5.4×10^3 man-rems per year in 2000.

4. Nuclear Systems

The growth rate of the use of nuclear energy in Scenario IV is the same as that of Scenario II up to the year 1985. It then levels off at 11.37 quads per year (1.2×10^{19} J). For light water reactors this is approximately equal to 124 GWe-year per year. The projected radioactive material emission rates for the entire nuclear fuel cycle for Scenario IV through 1985 is the same as that projected for Scenario II. After 1985, the projected emission rates are based on a constant nuclear power utilization rate of 124 GWe.

a. Mining

The projected radon atmospheric release rates for the uranium mining requirements are about 3 mCi/s in 1985 and 2.1 mCi/s in the year 2000. The amount of radioactivity from the lead-210, distributed in the environment from the radon-222 released, is estimated at about 150 Ci by 1985 and about 560 Ci by the year 2000.

The projected radon population exposure doses are 550 man-rems per year in 1985 and 580 man-rems per year in 2000.

b. Milling

The total radon-222 escape rates from milling operations and from the accumulated tailings piles are estimated at 6,600 Ci per year in 1985 and 15,000 Ci per year in the year 2000. The lead-210 activity in the environment created by the release of radon-222 from the mill site is estimated at about 11 Ci by 1985 and 60 Ci by the year 2000. The projected activity of the uranium released to the atmosphere is about 200 Ci per year in 1985 and about the same in the year 2000. The total activity of the uranium and uranium daughters released to the environment is estimated at about 1000 Ci by 1985 and about 4800 Ci by the year 2000.

The projected population exposure doses are 10 man-rems per year in 1985 and 22 man-rems per year in 2000 for radon; and 7000 man-rems per year in 1985 and about the same in the year 2000 for uranium.

c. Conversion to Uranium Hexafluoride

The projected release rates from the uranium conversion facilities are about 2 Ci per year in 1985 and about 2.1 Ci per year in the year 2000. The total activity of the uranium released is projected to be about 8 Ci by 1985 and about 40 Ci by the year 2000.

The projected population exposure doses are 1,300 man-rems per year in 1985 and 1,400 man-rems per year in 2000.

d. Uranium Enrichment

The projected atmospheric releases of uranium from the uranium enrichment facilities are about 1 Ci per year in 1985 and about the same in the year 2000. The projected uranium releases to streams are about 9 Ci per year in 1985 and about 9.5 Ci per year in 2000. The total activity of the uranium released to the environment is estimated at 47 Ci by 1985 and about 200 Ci by the year 2000.

The projected population exposure doses are 600 man-rems per year in 1985 and about the same in 2000.

e. Fuel Fabrication

The projected atmospheric release rates of the uranium from fuel fabrication facilities are about 0.05 Ci per year in 1985 and about the same in the year 2000. The total activity of the atmospherically released uranium is estimated at 0.24 Ci by 1985 and about 1 Ci by the year 2000.

The projected population exposure doses are 30 man-rems per year in 1985 and about the same in 2000.

F. Reactor Operations

The projected krypton-85 release rates for reactor operations are estimated at 1.7 x 10^6 Ci per year in 1985 and 1.8 x 10^6 Ci per year in the year 2000. The total activity of the released krypton-85 is estimated at 7.1 x 10^6 Ci by 1985 and 1.9 x 10^7 Ci by the year 2000.

The projected xenon-133 release rates are 3.1 x 10^6 Ci per year in 1985 and 3.3 x 10^6 Ci per year in the year 2000.

The projected carbon-14 release rates are 1,200 Ci per year in 1985 and about the same in 2000. The total activity of the released carbon-14 is estimated at 5,500 Ci in 1985 and 24,000 Ci in 2000.

The projected tritium atmospheric release rates are 7.1 x 10^4 Ci per year in 1985 and 7.5 x 10^4 Ci per year in the year 2000. The projected tritium stream release rates are 6.4 x 10^5 Ci per year in 1985 and 6.7 x 10^5 Ci per year in the year 2000. The projected total tritium release rates to the environment are 7.1 x 10^5 Ci per year in 1985 and 7.5 x 10^5 Ci per year in the year 2000. The projected total activity of the tritium releases is estimated at 3 x 10^6 Ci by 1985 and 8.3 x 10^6 Ci by the year 2000.

The estimated iodine-131 release rates are one curie to a few hundred curies per year for the years from 1985 through 2000.

The projected population exposure doses in man-rems per year are as follows:

Radionuclide	Man-Rems/Year	
	1985	2000
Krypton-85 (local air)	14	14
Krypton-85 (macroregional)	1 x 10^{-8}	1.4 x 10^{-8}
Xenon-133 (local air)	25	26
Carbon-14 (local air)	0.02	0.02
Carbon-14 (macroregional)	0.2	0.2
Tritium (local air)	0.9	0.9
Tritium (local fallout)	70	80
Tritium (local water)	5,000	5,000
Tritium (macroregional)	440	560
Iodine-131 (local air)	5	5

G. Spent-Fuel Reprocessing

The projected radionuclide releases of fuel reprocessing operations are as follows:

Radionuclide	Ci/yr 1985	 2000
Atmospheric releases		
Krypton-85	4×10^7	4.2×10^7
Carbon-14	1,200	1,200
Tritium	2.6×10^5	2.7×10^5
Iodine-129	0.1	0.1
Iodine-131	7	7.4
Other fission products	100	110
Actinides	0.5	0.5
Stream releases		
Tritium	4.7×10^5	5×10^5
Ruthenium-106	470	500

The total activity of the released krypton-85 is estimated at 1.7×10^8 Ci by 1985 and 4.1×10^8 Ci by the year 2000. The total activity of the released carbon-14 is estimated at 9,500 Ci in 1985 and 24,000 Ci in 2000. The total activity of all the released tritium is estimated at 1.3×10^7 Ci by 1985 and 2.9×10^7 Ci by the year 2000.

The projected population exposure doses in man-rems per year are as follows:

Radionuclide	Man-Rems/Year 1985	 2000
Krypton-85 (local air)	320	340
Krypton-85 (macroregional)	2.5×10^{-7}	3×10^{-7}
Carbon-14 (local air)	0.02	0.02
Carbon-14 (macroregional)	0.1	0.2
Tritium (local air)	50	50
Tritium (local fallout)	2,700	2,800
Tritium (local water)	3,500	3,800
Tritium (macroregional)	1.6×10^5	2×10^5
Iodine-129 (local air)	0.06	0.06
Iodine-131 (local air)	0.9	0.9
Ruthenium-106 (local water)	300	320
Actinides (local air)	2	2

The projected production rates of the radioactive fission products that are not released to the environment are 1.5×10^{10} Ci per year in 1985 and 1.6×10^{10} Ci per year in the year 2000. The total activity of the accumulated waste fission products is estimated at 3×10^{10} Ci by 1985 and 4.5×10^{10} Ci by the year 2000. The estimated actinide activity produced is 2.4×10^{6} Ci per year in 1985 and 3.5×10^{6} Ci per year in the year 2000. The total accumulated actinide activity is estimated at 1×10^{7} Ci by 1985 and 2.7×10^{7} Ci by the year 2000.

F. Energy Scenario V Emissions and Effects

1. Coal

a. Mining and Preparation

The projected coal utilization is lower for Scenario V than for any other energy scenario. The projected radon releases for all coal requirements are as follows:

	Ci/yr		
Year	Radon-222	Radon-220	Total
1985	57	42	99
2000	97	71	168

The projected population exposure doses from the radon-222 releases are 1.3 man-rems per year in 1985 and 2.1 man-rems per year in 2000.

b. Direct Combustion for Electric Power

The projected radioactive material releases are as follows:

	Ci/yr	
Radionuclide	1985	2000
Stack release:		
Radon-222	145	124
Radon-220	122	105
Uranium-238	0.7	0.6
Uranium-238 + daughters	8.8	7.8
Thorium-232	0.5	0.5
Thorium-232 + daughters	4.8	4.1
Potassium-40	1.1	1
Ash pile releases		
Radon-222	5,500	1.6×10^{4}

The projected population exposure doses from the above releases are as follows:

Radionuclide	Man-Rems/Year	
	1985	2000
Radon-222	400	1,000
Uranium-238	31	26
Thorium-232	6	6
Potassium-40	4.4×10^{-3}	4×10^{-3}
Polonium-210	0.6	0.5

c. Gasification

The projected coal gasification energy levels are the same as Scenario II. The projected radioactive material releases are as follows:

Radionuclide	Ci/yr	
	1985	2000
Stack releases		
Radon-222	15	57
Radon-220	20	75
Uranium-238	1.5×10^{-2}	5.5×10^{-2}
Uranium-238 + daughters	0.11	0.41
Thorium-232	4×10^{-3}	1.5×10^{-2}
Thorium-232 + daughters	2.8×10^{-2}	0.1
Potassium-40	6×10^{-3}	2.2×10^{-2}
Ash pile releases		
Radon-222	580	3,300

The projected population exposure doses, assuming a local population of 2×10^5 people within 80 km of all gasification facilities, are as follows:

Radionuclide	Man-Rems/Year	
	1985	2000
Radon-222	2	12
Uranium-238	3×10^{-2}	1×10^{-1}
Thorium-232	2×10^{-3}	9×10^{-3}
Polonium-210	7×10^{-4}	3×10^{-3}
Radon-226	7×10^{-3}	3×10^{-2}
Potassium-40	1×10^{-6}	4×10^{-6}

d. Liquefaction

The projected coal liquefaction energy levels are the same as Scenario II. The projected radioactive material releases are as follows:

Radionuclide	Ci/yr	
	1985	2000
Stack releases		
Radon-222	5×10^3	1.1×10^5
Radon-220	2.7×10^3	5.9×10^4
Uranium-238	5	110
Uranium-238 + daughters	46	1×10^3
Thorium-232	1.4	30
Thorium-232 + daughters	16	160
Potassium-40		
A[illegible]e releases		
Radon-222	180	5,000

The projected population exposure doses, assuming a local population of 2×10^5 people within 80 km of all liquefaction facilities, are as following:

Radionuclide	Man-Rems/Year	
	1985	2000
Radon-222	4	100
Uranium-238	11	240
Thorium-232	0.9	19
Polonium-210	0.2	5
Radium-226	5.5	120
Potassium-40	5.6×10^{-4}	1.2×10^{-2}

2. Oil Shale

The projected shale oil energy levels are the same as Scenario II. The projected radioactive material releases to the atmosphere are as follows:

Radionuclide	Ci/yr 1985	Ci/yr 2000
Uranium-238	1.9	19
Radon-222	1.3×10^4	1×10^5
All other uranium-238 daughters	25	200
Thorium-232	0.5	4.1
Radon-220	3.2×10^3	2.6×10^4
All other thorium-232 daughters	4	33
Potassium-40	120	970

The projected population exposure doses, assuming a local population of 80,000 people within 80 km of all oil shale processing facilities, are as follows:

Radionuclide	Man-Rems/Year 1985	Man-Rems/Year 2000
Radon-222	3.8	30
Radium-226	1.8	14
Uranium-238	1.7	13
Thorium-232	0.1	1
Polonium-210	3.5×10^{-2}	0.3
Potassium-40	9.6×10^{-3}	7.8×10^{-2}

3. Geothermal

The projected geothermal developments for this scenario are the same as those for Scenario III. The projected radon releases are 13,000 to 32,000 Ci per year in 1985 and 53,000 to 130,000 Ci per year in 2000. The projected population exposure doses from these releases are 230 to 580 man-rems per year in 1985 and 950 to 2,300 man-rems per year in 2000.

4. Nuclear Systems

The growth rate of the use of nuclear energy for Scenario V is the same as that for Scenario III, up to the year 1985. After 1985, the number of additional power plant units per year starts to decrease, leveling out at 24.3 quads per year (2.56×10^{19} J) in the year 2000. The nuclear energy utilization rate in 2000 is equivalent to 264 GWe.

a. Mining

The projected radon atmospheric release rates for the uranium mining requirements are about 2.6 mCi/s in 1985 and about 4.8 mCi/s in 2000. The amount of radioactivity from the lead-210, distributed in the environment from the radon-222 released, is estimated at about 170 Ci to 180 Ci by 1985 and about 840 Ci by the year 2000.

The projected radon population exposure doses are 130 man-rems per year in 1985 and 2[illegible] man-rems per year in 2000.

b. Milling

The total radon-222 escape rates from milling operations and from the accumulated tailings piles are estimated at 7,900 Ci per year in 1985 and 27,000 Ci per year in the year 2000. The lead-210 activity in the environment created by the release of radon-222 is estimated at 13 Ci by 1985 and 95 Ci by the year 2000. The projected activity of the uranium released to the atmosphere is about 250 Ci per year in 1985 and about 500 Ci per year in the year 2000. The total activity of the uranium and uranium daughters released to the environment is estimated at about 1,200 Ci by 1985 and about 8,000 Ci by the year 2000.

The projected population exposure doses are 11 man-rems per year in 1985 and 40 man-rems per year in 2000 for radon; and 9,000 man-rems per year in 1985 and 18,000 man-rems per year in 2000 for uranium.

c. Conversion to Uranium Hexafluoride

The projected release rates from the uranium conversion facilities are about 3 Ci per year in 1985 and about 5 Ci per year in the year 2000. The total activity of the uranium released is projected to about 11 Ci by 1985 and about 68 Ci by the year 2000.

The projected population exposure doses are 2,000 man-rems per year in 1985 and 3,300 man-rems per year in 2000.

d. Uranium Enrichment

The projected atmospheric releases of uranium from the uranium enrichment facilities are about 1 Ci per year in 1985 and about 2 Ci per year in the year 2000. The projected releases to streams are about 11 Ci per year in 1985 and about 20 Ci per year in 2000. The total activity of the uranium released to the environment is estimated at 53 Ci by 1985 and 340 Ci by the year 2000.

The projected population exposure doses are 660 man-rems per year in 1985 and 1,300 man-rems per year in 2000.

e. Fuel Fabrication

The projected atmospheric release rates of the uranium from fuel fabrication facilities are about 0.06 Ci per year in 1985 and 0.1 Ci per year in 2000. The total activity of the atmospherically released uranium is estimated at 0.25 by 1985 and 1.6 Ci by the year 2000.

The projected population exposure doses are 40 man-rems per year in 1985 and 70 man-rems per year in 2000.

f. Reactor Operations

The projected krypton-85 release rates for reactor operations are estimated at 2 x 10^6 Ci per year in 1985 and 3.8 x 10^6 Ci per year in the year 2000. The total activity of the released krypton-85 is estimated at 8 x 10^6 Ci by 1985 and 3.5 x 10^7 Ci by the year 2000.

The projected xenon-133 release rates are 3.8 x 10^6 Ci per year in 1985 and 7 x 10^6 Ci per year in the year 2000.

The projected carbon-14 release rates are 1,400 Ci per year in 1985 and 2,600 Ci per year in 2000. The total activity of the released carbon-14 is estimated at 6,300 Ci in 1985 and 40,000 Ci in 2000.

The projected tritium atmospheric release rates are 8.7 x 10^5 Ci per year in 1985 and 1.6 x 10^6 Ci per year in 2000. The projected tritium stream release rates are 7.8 x 10^5 Ci per year in 1985 and 1.4 x 10^6 Ci per year in 2000. The projected tritium release rates to the environment are 8.7 x 10^5 Ci per year in 1985 and 1.6 x 10^6 Ci per year in 2000. The projected total activity of the tritium releases is estimated at 3.4 x 10^6 Ci by 1985 and 1.3 x 10^7 Ci by the year 2000.

The estimated iodine-131 release rates are one curie to a few hundred curies per year in 1985, and one curie to several hundred curies per year in the year 2000.

The projected population exposure doses in man-rems per year are as follows:

Radionuclide	Man-Rems/Year	
	1985	2000
Krypton-85 (local air)	16	30
Krypton-85 (macroregional)	1.3×10^{-8}	2.9×10^{-8}
Xenon-133 (local air)	30	60
Carbon-14 (local air)	0.03	0.05
Carbon-14 (macroregional)	0.2	0.5
Tritium (local air)	1	2
Tritium (local fallout)	90	170
Tritium (local water)	6,000	11,000
Tritium (macroregional)	540	1,200
Iodine-131 (local air)	5	10

8. Spent-Fuel Reprocessing

The projected radionuclide releases of fuel reprocessing operations are as follows:

Radionuclide	Ci/yr	
	1985	2000
Atmospheric releases		
Krypton-85	4.9×10^{7}	9×10^{7}
Carbon-14	1,400	2,600
Tritium	3.2×10^{5}	5.8×10^{5}
Iodine-129	0.14	0.26
Iodine-131	9	16
Other fission products	130	240
Actinides	0.6	1.1
Stream releases		
Tritium	5.8×10^{5}	1.1×10^{6}
Ruthenium-106	580	1,100

The total activity of the released krypton-85 is estimated to be 2×10^{8} Ci by 1985 and 8.2×10^{8} Ci by the year 2000. The total activity of the released carbon-14 is estimated at 6,300 Ci in 1985 and 40,000 Ci in 2000. The total activity of all the released tritium is estimated at 1.7×10^{7} Ci by 1985 and 6.6×10^{7} Ci by the year 2000.

The projected population exposure doses in man-rems per year are as follows:

Radionuclide	Man-Rems/Year 1985	 2000
Krypton-85 (local air)	390	720
Krypton-85 (macroregional)	3×10^{-7}	7×10^{-7}
Carbon-14 (local air)	0.03	0.05
Carbon-14 (macroregional)	0.2	0.5
Tritium (local air)	60	110
Tritium (local fallout)	3,000	6,000
Tritium (local water)	4,400	7,500
Tritium (macroregional)	2×10^{5}	4.4×10^{5}
Iodine-129 (local air)	0.09	0.2
Iodine-131 (local air)	1	2
Ruthenium-106 (local water)	370	700
Actinides (local air)	2.4	4

The projected production rates of the radioactive fission products that are not released to the environment are 1.9×10^{10} Ci per year in 1985 and 3.4×10^{10} Ci per year in the year 2000. The total activity of the accumulated waste fission products is estimated at 3.6×10^{10} Ci by 1985 and 9.8×10^{10} Ci by the year 2000. The estimated actinide activity produced is 2.9×10^{6} Ci per year in 1985 and 5.3×10^{6} Ci per year in the year 2000. The total accumulated actinide activity is estimated at 1.1×10^{7} Ci by 1985 and 5.2×10^{7} Ci by the year 2000.

VI DISCUSSION OF RESULTS

The radioactive materials release rates and the population exposure doses for coal, oil shale, geothermal, and nuclear resources utilization in four projected expanded energy programs were calculated for the years 1985 and 2000 and presented in the previous section. These results were based on radioactive material concentrations that varied widely, release rates that also varied widely, and exposure dose calculations where many of the equation input values were speculative rather than established. Where data were not available, estimates were made to facilitate the calculation of results. For example, it was assumed that 5% of the radon generated from radium-226 at the coal ash pile escapes to the atmosphere. This assumed escape rate may be several times too high or it may be too low. Also, because geothermal, coal gasification and liquefaction, and shale oil extraction energy systems are not yet established industries, their future locations with respect to surrounding population densities are not known. To fill the calculation gap, rough estimates of potential exposed populations were necessary. The calculated population exposure doses, therefore, are not for the purpose of projecting health effects, but rather for projecting the relative importance of the radioactive materials released to the environment.

For nonnuclear energy systems, the dominant radionuclide contributing to radiation exposure doses is radon-222. The energy system contributing a major portion of the radon-222 population exposure doses is the combustion of coal to produce electricity. The major source of radon-222 from this system is the coal ash piles--the stack releases of radon-222 from coal combustion being relatively insignificant. The coal ash piles would be the major radon-222 release source for the coal combustion for electricity energy system even if the radon release were 1% rather than the assumed 5%.

On a per unit of energy basis, the geothermal energy system is also a major contributor to radon-222 exposure doses. For example, in Scenario IV where the projected geothermal and the coal combustion for electricity levels were similar, the population exposure doses attributed to the release of radon-222 from these energy systems were of the same order of magnitude.

Radon escapes also from the coal ash piles of coal gasification and coal liquefaction facilities; however, the accumulated ash from both these facilities is less than that from coal combustion. In addition, it was assumed that the coal gasification and liquefaction facilities were located in more sparsely populated areas. For example, if the coal liquefaction expansion rate indicated in Scenarios II, IV, and V were to continue, and these liquefaction plants were located in more densely populated areas, the population radon-222 exposure doses from these plants could exceed those from coal-burning power plants.

The other radioactive materials released from these nonnuclear energy facilities are the uranium series radionuclides, the thorium series radionuclides, and potassium-40. Because these radionuclides are either in liquid, solid, or particulate form, the waste or emissions control systems of these facilities limit their escape to the environment and the population radiation exposure doses from these radionuclides are relatively insignificant.

The population exposure doses derived from the extraction of shale oil are relatively insignificant. Radon-222 will escape from the waste shale piles, but the radium-226 content in oil shale is very low, and hence, the radon escape rate from the massive amounts of spent shale is expected to be slow.

For nuclear energy systems, the ranking order of the radionuclides contributing to radiation exposures is subject to the control technologies adopted. Based on the radionuclide release rates given in Section IV, the release of tritium from reactor operations and from spent-fuel reprocessing provided the greatest population exposure doses. This was followed by the population exposure doses from the escape of particulate uranium from milling operations, conversion facilities, enrichment facilities, and fuel fabrication facilities. Other radionuclides and sources contributing to the population doses in decreasing order of importance are: radon-222 from mining and milling operations, krypton-85 from spent fuel reprocessing and reactor operations, ruthenium-106 from spent fuel reprocessing operations, xenon-133 from reactor operations, and iodine-131 from reactor and spent-fuel reprocessing operations.

The relative importance of these radioactive emissions can be perceived by the following summation of the exposure doses derived from these radionuclides and their sources from Scenario IV.

Radionuclide and Source		Man-rems/year	
		1985	2000
Tritium	reprocessing	2.7×10^5	2.7×10^5
	reactor	5.5×10^3	5.6×10^3
	Tritium total	2.7×10^5	3.3×10^5
Uranium-238	milling	7×10^3	7×10^3
	conversion	1.3×10^3	1.4×10^3
	enrichment	660	660
	fabrication	30	30
	Uranium-238 total	9×10^3	9.1×10^3
Radon-222	mining	550	580
	milling	10	22
	Radon-222 total	560	600
Krypton-85	reprocessing	320	340
	reactor	14	14
	Krypton-85 total	330	350
Ruthenium-106	reprocessing	300	310
Xenon-133	reactor	25	26
Iodine-131 and Iodine-129 total		6	6
Actinides	reprocessing	2	2
Carbon-14	reactor	0.2	0.2
	reprocessing	0.2	0.2

For comparative purposes the population exposure doses for nonnuclear energy systems from Scenario IV may be used. For direct combustion of coal, the projected energy levels in 1985 and 2000 are sufficiently similar for direct comparisons. The 1985 projections for the remaining nonnuclear energy systems are omitted because of the relatively low energy levels projected The coal liquefaction and the geothermal energy levels in 2000 can be considered comparable. The projected energy level for coal gasification is lower by a factor of 3 and the projected energy level for shale oil is lower by a factor of 2. The projected population exposure doses for comparable projected energy levels for nonnuclear energy systems in Scenario IV are summarized as follows:

Energy System	Man-rems/year 1985	Man-rems/year 2000
Coal, direct combustion		
Radon-222	430	1200
Uranium-238	35	44
Thorium-232	7	9
Polonium-210	0.7	0.9
Coal gasification		
Radon-222	--	12
Coal liquefaction		
Radon-222	--	100
Uranium-238	--	240
Radium-226	--	120
Polonium-210	--	5
Shale oil		
Radon-222	--	30
Uranium-238	--	11
Radium-226	--	14
Geothermal		
Radon-222	--	2.1×10^3

As can be seen, the population exposure doses derived from nuclear energy systems, the direct combustion of coal, and the extraction of geothermal energy are comparable in magnitude. Although the projected coal liquefaction energy level for the year 2000 is comparable to that of direct coal combustion, the projected population exposure dose for coal liquefaction is considerably lower. The reasons for this lower dose are that the projected late development of the coal-liquefaction industry makes the accumulated coal ash less, and it was assumed that the population in the region of coal liquefaction plants will be lower than that in the region of coal-burning power plants.

The exposure doses received by individuals within 3 km of the accumulated ash from a 100,000 bbl/day liquefaction plant, however, would be relatively high. For example, if 5% of the radon escapes from the 30-year accumulation of ash for the case cited in the text, the annual radon release rate would be about 800 Ci/year. At this release rate the estimated lung exposure dose is about one rem per year at 3 km.

In the case of the direct combustion of coal, the total population exposure dose is divided among a large population because a large number of power plants are required to produce the projected energy levels. For this reason, the average individual exposure doses are relatively low. For example, if the number of people exposed were 30 million people, then the average individual exposure would be 0.07 millirem per year.

On the other hand, the exposure dose to people within 3 km of the ash pile of a 1000-MWe coal-combustion power plant could be relatively high. For example, if 5% of the radon escapes from the 30-year accumulation of ash for the 1000-MWe case cited in the text, the annual release rate would be about 700 Ci per year. At this release rate, the estimated lung exposure dose is about 0.04 rem per year at 3 km.

For the geothermal energy extraction case, the number and locations of the projected geothermal developments are not known. However, it can be anticipated that because the geothermal areas are generally located in the less populated western states, fewer people than in the case of direct coal combustion would be exposed. The result is that for the same total population exposure dose, the average individual exposure dose would be higher. For example, if only half the number (15 million) of people were exposed, the average individual exposure dose for geothermal radon exposures would be 1.5 millirem per year. For close-in exposure doses, the potential radon releases from each geothermal site must be separately assessed.

In the case of nuclear energy, a major part of the population exposure dose is from the release of tritium during spent-fuel reprocessing. The capacity of spent-fuel reprocessing plants is relatively large, and only a few would be necessary to meet the reprocessing requirements of the projected Scenario IV nuclear energy level for the year 2000. Thus, the average individual exposure doses among the local population could be relatively high. If it is assumed that the number of spent-fuel reprocessing facilities in the year 2000 for this scenario is five, then the average individual exposure dose for the projected 400,000 people drinking the downstream waters would be 9.5 millirems per year. The tritium total exposure dose received by individuals within 3 km of a reprocessing plant would be 1.4 rems per year. The average individual exposure dose among the local (within 80 km) population of 20 million people ($5 \times 4 \times 10^6$) from atmospheric tritium releases would be only 0.14 millirems per year.

The population exposure doses from the release of tritium from reactor operations are about a factor of 5 lower than that from spent-fuel reprocessing. Also because the total energy output is spread among a large number of reactors, the local exposure doses are lower by more than 2 orders of magnitude. Exposure doses from the shorter-lived xenon-133 and iodine-131 radionuclide releases, on the other hand, are higher, but the population exposure doses from these two radionuclides are, nevertheless, relatively insignificant.

The radon releases from uranium mill tailings piles (totalling 1.5×10^4 Ci/yr for the year 2000) are comparable to the coal combustion ash pile release (totaling 1.7×10^4 Ci/yr for the year 2000). The higher population exposure doses derived for coal ash pile releases are due to the greater number of people that are exposed by the radon releases from coal burning power facilities.

The uranium mill is also the facility releasing the greatest quantity of uranium particulates to the atmosphere and the source of the major uranium population exposure dose. Most of the atmospheric uranium releases are from the drying process. Although the amount of uranium radioactivity released is substantially lower than that of radon, the dose conversion factor for uranium is over two orders of magnitude higher; this results in the relatively high uranium population exposure doses.

On a local basis, the size of a mill tailings pile is independent of the energy scenarios and a large mill with a long plant life will accumulate a large tailings pile. The exposure doses received by individuals close-in to those large tailings piles could be relatively high.

The other radionuclides listed do not contribute significantly to population exposure doses. Other natural radionuclides that are not listed here are also released to the environment by nonnuclear energy systems, but their contribution to population exposure doses are even less significant. The same could be said about the other radionuclides released from nuclear facilities that are not listed here.

The findings with respect to radiological quality assurance aspects are the wide differences in the data (both estimated and measured) on the release rates of the various radionuclides in nuclear energy systems and the sparseness of the data on radioactive material releases from nonnuclear energy systems. For nuclear systems, better assessments of the tritium generation rates in the coolant and in the fuel, and the subsequent release rates to the atmosphere and to streams are required. Better assessments of the escape rates during mining (particularly open-pit mining) and milling operations, and from the mill tails are also required. Assessments of the uranium atmospheric releases from uranium mills, conversion plants, enrichment plants, and fabrication plants are required, in addition to assessments of reprocessing radioactive releases once reprocessing operations are reestablished.

For nonnuclear energy systems radon releases appear to be the potential predominant source of population exposure, and for this reason measurements of radon releases for coal ash piles, spent oil shale piles, and from geothermal resources need to be assessed.

Finally, the problems associated with the high-level radioactive wastes from spent-fuel reprocessing are yet to be resolved, and they were not addressed in this study.

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